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सारांश

न्यूट्रान स्रोत विविध प्रकार के होते हैं जो नाभिकीय रिएक्टर, कण त्वरक एवं प्रयोगशाला स्रोत जैसी उत्पादन की पद्धति पर निर्भर करते हैं। न्यूट्रान स्रोत उनकी ऊर्जा, फ्लक्स, आकार इत्यादि के अनुसार मूलभूत तथा अनुप्रयुक्त विज्ञान, न्यूट्रान प्रकीर्णन प्रयोग एवं तेल के कुएं खोदने, कोयले का खनन तथा संसाधन, अयस्क संसाधन जैसे उद्योगों में विभिन्न अनुप्रयोगों में प्रयोग में लाए जाते हैं। रिएक्टर, त्वरक, भुक्तशेष ईंधन संसाधन संयंत्रों, नाभिकीय ईंधन चक्र प्रचालन जैसी नाभिकीय संस्थापनाओं में कार्यरत कार्मिकों और वे व्यक्ति जो तेल परिष्करण, तेल के कुएं खोदने, कोयले का खनन एवं संसाधन, अयस्क संसाधन आदि जैसे विभिन्न उद्योगों में कार्यरत हैं उनका भी न्यूट्रान उद्‌भासन यदि कोई हो, के लिए मानीटरन करने की आवश्यकता है। न्यूट्रान मानीटरन विशेष रूप से आवश्यक है क्योंकि न्यूट्रान का भार गुणांक गामा किरणों से काफी अधिक होता है और यह ऊर्जा के साथ परिवर्तित भी होता है। विकिरणात्मक भौतिकी एवं सलाहकार प्रभाग न्यूट्रान क्षेत्रों में कार्यरत कार्मिकों के मानीटरन से जुडा है। 70 संस्थाओं (पऊवि एवं गैर पऊवि) के लगभग 2100 कार्मिकों का त्रैमासिक आधार पर मानीटरन किया जाता है।

देश में किए जा रहे न्यूट्रान कार्मिक मानीटरन, ठोस अवस्था नाभिकीय ट्रैक संसूचक (SSNTD) तकनीक पर आधारित है। इस तकनीक में, परिक्षिप्त प्रोटान उत्पन्न करने के लिए न्यूट्रानों की CR-39 पालीमर में हाइड्रोजन के साथ अभिक्रिया होती है। यह प्रोटान पालीमर में क्षति पहुंचाते हैं, जिसके कारण वे विवर्धित होकर विद्युतरासायनिक उत्कीर्णन (ECE) करने पर ट्रैक्स के रूप में प्रकट होते हैं। वर्ष 1990 में प्रारंभ होने के बाद SSNTD पर आधारित न्यूट्रान मात्रामिति प्रणाली में महत्वपूर्ण विकास हुआ है। विकास में ट्रैक्स की गणना, 10 mSv से अधिक समतुल्य मात्रा के मूल्यांकन हेतु उच्च तापमानों पर रासायनिक उत्कीर्णन (CE) का प्रारंभ किया जाना एवं CR-39 संसूचकों के कर्तन हेतु कार्बन लेसर का प्रयोग शामिल है। संपूर्ण मात्रा मूल्यांकन प्रक्रिया को मानकीकृत किया गया, जिसमें अंतरराष्ट्रीय मानकीकरण संगठन (ISO) की सिफारिशों के अनुसार अंशांकन एवं न्यूट्रान मात्रामापियों की निष्पादन जांच शामिल है। न्यूट्रान कार्मिक मानीटरन में इन सभी विकासों की विस्तृत चर्चा इस रिपोर्ट में की गई है।

ABSTRACT

Neutron sources are of different types depending upon the method of production such as nuclear reactors, particle accelerators and laboratory sources. Neutron sources depending upon their energy, flux, size etc. are used for variety of applications in basic and applied sciences, neutron scattering experiments and in industry such as oil well – digging, coal mining & processing, ore processing etc. Personnel working in nuclear installations such as reactors, accelerators, spent fuel processing plants, nuclear fuel cycle operations and those working in various industries such as oil refining, oil well – digging, coal mining & processing, ore processing, etc. need to be monitored for neutron exposures, if any. Neutron monitoring is especially necessary in view of the fact that the radiation weighting factor for neutron is much higher than gamma rays and also it varies with energy. Radiological Physics & Advisory Division is involved in monitoring of personnel working in neutron fields. Around 2100 workers from 70 institutions (DAE and Non-DAE) are monitored on a quarterly basis.

Neutron personnel monitoring, carried out in the country is based on Solid State Nuclear Track Detection (SSNTD) technique. In this technique, neutrons interact with hydrogen in CR-39 polymer to produce recoil protons. These protons create damages in the polymer, which are enlarged and appear as tracks when subjected to electrochemical etching (ECE). These tracks are counted in an optical system to evaluate the neutron dose. The neutron dosimetry system based on SSNTD has undergone a significant development, since it was started in 1990. The development includes upgradation of image analysis system for counting tracks, introduction of chemical etching (CE) at elevated temperatures for evaluation of dose equivalents above 10 mSv and use of carbon laser for cutting of CR-39 detectors. The entire dose evaluation process has been standardized, which includes calibration and performance tests of neutron dosemeter as per International Organization for Standardization (ISO) recommendations. All these developments in neutron personnel monitoring have been discussed in details in this report.

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1. INTRODUCTION

Neutron sources are of different types depending upon the energy of the neutrons emitted by the source, the rate of neutrons emitted by the source and the method of production. Examples of some neutron sources are nuclear reactors, accelerators and laboratory sources. Dedicated neutron sources like research reactors, accelerators and spallation sources produce free neutrons for use in material science and neutron scattering experiments. Neutrons find use in a diverse field of applications such as physics, biology, chemistry, engineering, medicine, nuclear weapons, petroleum exploration, nuclear power. Mono-energetic neutrons which are produced in neutron generators / accelerators are used in nuclear physics studies, development of spectrometers, neutron metrology, material damage test, activation analysis, neutron radiography, cancer therapy etc. Unique properties of neutrons, such as neutron thermalisation in matter, ability to induce activity and preferential absorption of neutrons by some elements, make it very useful in various industries like Oil and gas (fluid flow), Oil logging (delineation of deposit, in situ assay), Mineral processing (slurry analysis, density, weight and level gauging), manufacturing industries (moisture content) etc.

Personnel working in nuclear installations such as reactors, accelerators, spent fuel processing plants, nuclear fuel cycle operations, and those handling neutron sources in various industries such as oil refining, oil well – digging, coal mining & processing, ore processing, etc. may be exposed to neutron radiation. To evaluate the radiation exposure for these workers and determine the adequacy of radiation safety measures during operations, radiation monitoring is carried out.

Personnel monitoring program for external radiation exposure is intended to provide information for the optimization of protection, to demonstrate that the radiation dose received by the workers does not exceeds the prescribed dose limits recommended by the regulatory authority. It gives information of doses received during particular activities in reactor, accelerator and well-logging and verifies the shielding adequacy of work place monitoring. For radiation workers involved in the field of neutron radiation, personnel monitoring is based on the solid state nuclear track detector (SSNTD). Radiological Physics & Advisory

Division (RPAD) is involved in carrying out country wide personnel monitoring of radiation workers in neutron fields. Around 2100 workers from 70 institutions (DAE as well as Non-DAE) are monitored on a quarterly basis.

2. NEUTRON PERSONNEL MONITORING IN INDIA

Neutron personnel monitoring started in India since 1970 using Kodak NTA nuclear emulsion films. The main drawback of NTA emulsion was its susceptibility to extreme climatic conditions, i.e. post-irradiation fading of proton tracks with temperature and humidity. The emulsion was sensitive to gamma rays and the evaluation with microscope was quite tedious and time consuming. Moreover, the threshold energy of Kodak NTA film for neutrons was 500 keV. The films were also energy dependent. Due to the above drawbacks, it was necessary to have a different detector for neutron personnel monitoring system.

CR-39 Solid State nuclear track detector gained widespread acceptance for personnel neutron monitoring in 1980s after the studies of Tommasino et al, Hankins et al, Griffith et al and Dajko [1-4] on this detector. CR-39 detectors have neutron threshold at 100 keV with relatively flat energy response. It does not respond to beta and gamma radiation. Feasibility studies of CR-39 for application in fast neutron personnel monitoring in our division began in 1990 and a BARC report was published in the same year [5]. The SSNTD based personnel monitoring system was first started in 1991 for DAE units. Kodak NTA films were gradually phased out and since 1999, CR-39 detectors based neutron dosemeter are being used for fast neutron personnel monitoring throughout the country for DAE and non-DAE institutions [6].

The previous report [5] discusses the properties of CR-39, etching mechanism, based on available literature. It also presented data on preliminary studies on background and sensitivity of CR-39 detector. The track counting was based on microfische reader. The report also discusses the ageing and environmental effects on background tracks.

Constant endeavor to improve the performance of the detector and standardize the neutron dosimetry system has resulted in many developments. In the past two decades, developments on different aspects of neutron dosimetry system have taken place.

The present report discusses the development in the instrumentation, etching process and evaluation procedure of CR-39 detectors. It highlights the up-gradation of the image analysis system for track counting and introduction of chemical etching method for over-exposure cases (≥10mSv). In addition to this, optimization of electro-chemical etching technique, standardization of calibration procedures based on ISO recommendations and studies on angular response have been presented in this report.

3. SOLID STATE NUCLEAR TRACK DETECTOR (SSNTD)

Solid State Nuclear Track Detection (SSNTD) is a technique of recording tracks of ionizing particles in insulating solids and was discovered by Young in 1958. Since then, many insulating materials have been tested and CR-39, a special type of plastic was found to be most useful for nuclear track detection. The chemical name for CR-39 is poly-allyl-diglycol carbonate (PADC) with chemical formula $C_{12}H_{18}O_7$. CR-39 stands for Columbia Resin (trade name). It is an optically clear plastic and also finds great application as a major component in copolymers used for lenses in spectacles. It is a track detector where tracks are formed due to the interaction of charged particles like protons, alpha and heavy ions with the polymer bonds of PADC.

Its popularity as neutron detector is due to the fact that neutron interacts with the hydrogen in CR-39 producing recoil protons from elastic collisions. The energy deposited by protons creates damage (breakage of bonds in the polymer) in this detector. These damages get enlarged and appear as tracks if subjected to etching and are viewed through an optical imaging system [7]. CR-39 shows response to wide range of neutron energies using recoil proton mechanism. It is insensitive to beta and gamma radiation in a wide range of doses. These properties of CR-39 make it a versatile neutron detector as neutrons are always accompanied by gamma radiation. There is no post irradiation fading of damaged tracks due to environmental conditions. The neutron energy threshold for this detector is 100 KeV which makes it most suitable for neutron personnel monitoring in reactor environments and fuel reprocessing facilities. The properties of CR-39 mentioned above are exploited to assemble it, as a neutron detector.

However, a crucial characteristic of CR-39 detectors is the background track density. This background can be attributed to (i) alpha exposure from radon during the storage of the detector (ii) cosmic radiations and (iii) surface defects and contaminants introduced during the manufacturing process. There is a considerable increase in background of CR-39 with time (aging) due to environmental conditions that prevail during storage of these foils from the time of manufacturing to the time of processing of the foils if it is not properly stored. In order to reduce the background tracks due to environmental conditions, CR-39 detectors are stored in a refrigerator and covered with thick black polythene at our laboratory.

4. CHARACTERISTICS OF A IDEAL NEUTRON PERSONNEL DOSEMETER

Neutron dosemeter can be of different types with its own advantage and disadvantages, however an ideal personnel neutron monitor should have the following characteristics:

1. It's response should be linear in the dose equivalent range applicable for personnel dosimetry
2. It's neutron energy response should be proportional to dose equivalent response i.e. response independent of energy over a considerable range of neutron energies.
3. It should be insensitive to other types of radiation like beta, x-rays and gamma rays in particular, which normally accompanies neutrons.
4. It should have a good signal stability with little/no fading due to ambient conditions.
5. It should not be toxic to the wearer.
6. It should be rugged, easy to handle for a large scale of monitoring purposes and be reasonably inexpensive.

CR-39 SSNTD is found to comply with most of the requirement of a personnel dosimeter mentioned above. However, it has the disadvantage of background tracks which increases with time and hence it has a limited shelf life. The detector is not re-usable. It is imported and costly. Still, it is one of the best detector for neutron dosimetry which has the advantages of being light weight, small in size, responds to wide range of neutron energy, insensitive to high doses of beta and gamma, linear response to dose and negligible fading. Above all, the tracks produced due to neutron irradiation serve as a permanent record and can be stored for years without losing any tracks. In most of the countries world wide it is the choice of detector for personnel neutron monitoring.

5. DETAILS OF NEUTRON PERSONNEL DOSIMETER

The neutron badge used for personnel neutron monitoring comprises of a CR-39 detector of dimensions 3 cm x 3cm x 0.0625 cm, with a 1mm thick polyethylene radiator of similar dimension in the front, sealed together in an air-tight triple laminated aluminized pouch. The CR-39 detector used in the badge is of dosimetric grade, with 32 h curing cycle, manufactured by M/s Pershore Moulding, U.K. The detector is received from the manufacturer in the form of a sheet of dimension 47 cm x 30 cm x 0.0625 cm. The bigger sheet is cut into 3 cm x 3 cm pieces with CO_2 laser. The polyethylene radiator in the badge provides enhanced sensitivity for track detection due to recoil protons produced by the interaction of neutron with radiator. The aluminized pouch protects the detector from ambient conditions, makes the detector dust free during handling and prevents entry of atmospheric radon/alpha particles which may produce tracks in the detector. The sealed pouch is further loaded in a plastic holder having a clip for the wearer. The photograph of all the components of the neutron badge along with the assembled badge is shown in Fig.1. The frequency of monitoring service is quarterly for personnel working in neutron fields.

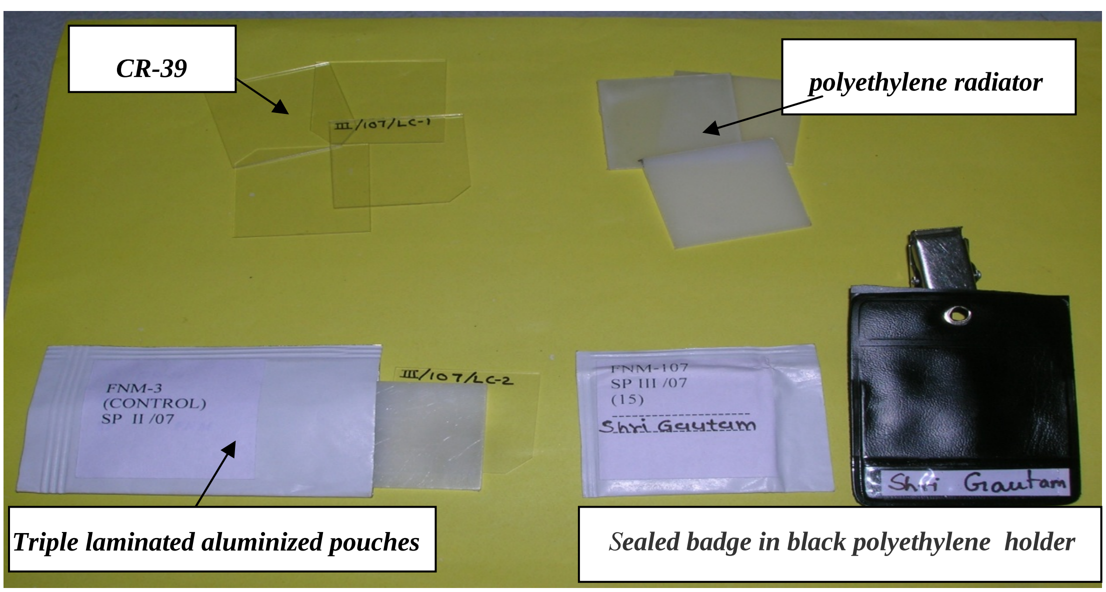


Fig.1: Photograph of different components of neutron badge along with the assembled badge

6. MECHANISM OF TRACK FORMATION IN CR-39 DETECTOR

Neutrons interact with the polythene radiator as well as CR-39 detector of the badge through elastic scattering with hydrogen and produces recoil protons. These protons deposit their energy to CR-39 detector and produces damage in the detector. The damages are nothing but the breakage of the molecular bonds in the detector. These damage sites are known as tracks. The recoil protons have nearly the same energy as the incident neutrons. The diameter of the tracks depends on the incident neutron energy i.e. lower the energy, smaller will be the diameter and vice versa. To magnify the tracks and to view through optical imaging system, different etching techniques are employed.

Etching is a process by which tracks are magnified using alkaline solution. The alkaline solution penetrates faster at the damaged sites than the rest of the detector. A track is enlarged only if the rate of etching along the track V_T, exceeds the rate at which the surface is etched V_B ($V_T/V_B > 1$). Fig.2 shows the track etch geometry of a perpendicularly incident charged particle on the detector. In this track formation model, as given by Tommasino and Harrison[8], the track etching rate, V_T is assumed to be constant and the surface etching rate V_B is isotropic. The track diameter, D and the length of the track, L depend essentially on the competitive effects of V_T and V_B. From the Fig.2, track diameter D can be derived

$$L = (V_T - V_B)\, t \quad \text{-----------------------------(1)}$$

Where t is the etching time, and

$$D = 2\, V_B\, t\, \sqrt{(V_T - V_B)/V_T + V_B)} \quad \text{----------(2)}$$

For $V_T = V_B$, the L=D=0

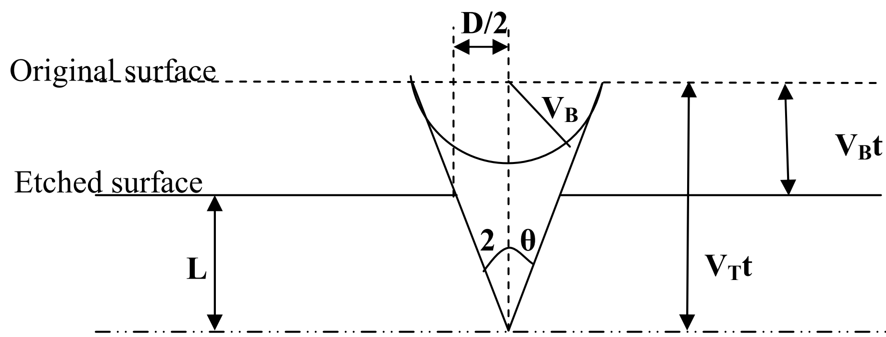


Fig.2. Track etch geometry for a normally incident particle (From Tommasino and Harrison, Radiation Protection Dosimetry,1985)

7. ETCHING TECHNIQUES

Different CR-39 based dosimetric systems can be employed for measurement of wide range of neutron doses generally encountered in neutron monitoring. The dosimetric systems used at different laboratories for neutron personnel monitoring employing SSNTD are diverse, with a wide variety of etching process, read out systems and holder designs [9]. There are several etching techniques such as chemical etching (CE), electro-chemical etching (ECE) and combination of both chemical and electrochemical techniques. These techniques can be used for enhancing the damaged tracks and counted with appropriate imaging system. In our laboratory to cover the wide dose range, two etching techniques are adopted; (i) electro-chemical etching (ECE) and (ii) chemical etching (CE). ECE is a two step etching process for neutron dose equivalents up to 10 mSv whereas CE is a single step process to cover the neutron dose equivalents above 10 mSv.

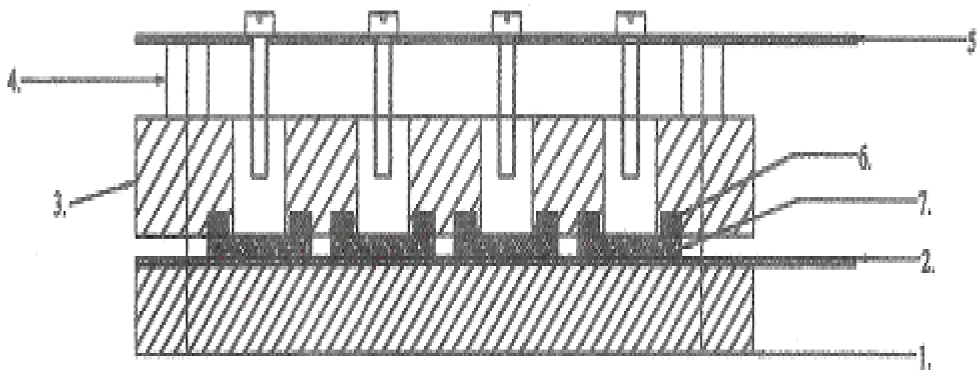
7.1 Electro Chemical Etching (ECE) technique

In our laboratory, we are following the two step elevated temperature ECE method developed by Tomasino et al[10-12]. Tracks of varying depths are produced depending upon the recoil proton energy. Application of electric field to chemical etching enlarges tracks even at small depths and makes it visible for counting at low magnification[13]. The ECE technique significantly improves the energy response of CR-39 detector and brings the energy threshold down to 100 keV. The CR-39 detectors are processed by ECE using a specially designed electro chemical etching cell (ECE cell). In this method, 16 detectors are processed at a time. On one side of the cell, a plain stainless steel plate is kept to serve as neutral electrode, while at the other side, small cavities filled with 7 N KOH solutions contain electrodes dipped into the KOH solution through which AC current is allowed to pass by applying high voltage. Schematic diagram of the cell along with its components is shown in Fig.3. Photograph of an ECE cell is shown in Fig 4. The detectors are mounted on the ECE Cell and etched in an incubator maintained at 60° C. Photograph of an incubator along with a high voltage power supply is shown in Fig 5. The ECE process is carried in two steps as follows:-

Step -1: Etching at low frequency of 100 Hz for 4 h at 1250 volts peak to peak constant potential. In this stage the damage tracks are marked.

Step-2: Etching at high frequency of 3.5 kHz at 1250 volts for 40 min duration. In this step the electrical stresses enlarge the tracks marked during low frequency. This initiates localized break downs at the track's tip and the resulting tracks look like trees and are large enough to be viewed easily with an imaging system.

At high frequency, the track etch velocity (V_T) is higher than the surface etch velocity (V_B) so that tracks of larger diameter are produced. Typical field strength of the ECE system using CR-39 foils of thickness 625 μm is 20 $kVcm^{-1}$.The etching method described above was optimized based on experiments carried out for various durations at low and high frequency[14]. Subsequent to etching, detectors are washed in running water thoroughly to remove all the alkali solution and then dried at room temperature for eight to ten hours. The washing is done to avoid the formation of white patches on the detector due to the presence of remnant KOH solution.



1. Nylon pressure plate (150mm x 150mm x 12mm)
2. S.S. electrode grid plate (bottom)
3. Acrylic plate (transparent) (150mm x 150mm x 16mm)
4. Nylon spacers
5. S.S. electrode grid plate (top)
6. Neoprene "O" rings (inside dia =15mm, outside dia=23mm, thickness=3mm)
7. CR-39 detectors 16 Nos.

Fig. 3: Schematic diagram of electrochemical etching cell

Fig 4: Photograph of ECE cell

Fig 5. Photograph of HV power supply and incubator maintained at 60°C- for ECE.

7.2 PC based Image Analysis System for ECE Technique

Manual method of counting has limited capability when measurements with higher accuracy and reproducibility are required. PC based image analyzers can overcome these shortcomings. Image analyzers are generally used for evaluation of track detectors for routine and research applications. Since there is a strong correlation between the measurable track parameters (area, diameter, eccentricity, etc) and the property of the particle inducing the track, it is important to use image analyzers that are capable of measuring the necessary parameter with an acceptable accuracy and reproducibility.

In an earlier version of imaging analyzer, the system consisted of an analog B/W CCD camera as imaging device and ISA frame grabber interfaced to a personal computer (25MHz PC-386 machine). The frame grabber digitized the analog signal from the CCD camera, stored the digitized data and converted the image back to the analog format for display on CCTV monitor. The digitized picture had resolution of 512 x 512 x 8 bit. Execution of the image analysis software was slower than the present system. The processing and counting of each detector would take 1-2 min. There was no provision in the software to change the track parameters such as diameter of the track (fixed at 70-100 micron) and roundness factor (fixed at 1.0). These limitations of the software used to eliminate many of the genuine tracks from the final count.

An upgraded PC based automatic image analysis system was therefore developed in collaboration with Electronics and Instrumentation Services Division, BARC [15]. This system is presently being used for the counting of neutron induced tracks in CR-39 detector following the ECE technique. The photograph of an upgraded image analysis system is shown in Fig. 6. The system consists of an analog B/W CCD video camera, interfaced to a PCI frame grabber with Video for Windows (VfW) driver for Pentium-IV (P-IV) computer. It takes 15 sec per detector for counting. The digitized picture is of 768 x 576 x 8 bit resolution. Hence, the spatial resolution of the image improved (by a factor of 1.7 approximately) using the present system (1pixel=15 micron). The camera with zoom lens and suitable light source is fixed in a metal box, practically cutting off the effect of any ambient light on the scene. The box has a small sliding tray on which the processed detector foil is mounted. In this system, before starting the actual counting, the track counting parameters are selected. Immediately following this, tracks in control detector are counted and stored. The net track count of the irradiated detectors can be determined by the software (subtracting the control reading from irradiated one) utilizing the stored control detector tracks without any manual intervention. This was not possible in the earlier imaging system and hence repeated counting of control detector was required. The software (based on VC++) scans through the image of the irradiated detectors for the tracks and displays net counts in terms of tracks per cm^{-2}. It also displays the average diameter of the net tracks. Fig.7 shows images of tracks in control and exposed CR-39 detectors, as seen through the image analysis system. The images and data can be stored against the detector number in a file in the present system.

7.3 Track Counting Parameters for ECE technique

The software of the image analysis system converts the captured image of the track of the detector into a binary image. The basic parameters which are computed for the tracks in the binary image, are area, perimeter and roundness factor. The tracks that are produced due to irradiation should ideally be round in shape and have a roundness factor close to that of a circle. Roundness factor is computed as $\frac{Area \times 4\pi}{(perimeter)^2}$ and is 1.0 for the perfect circle. The parameters are set in the software such that, only the tracks that fall within the set range of area and the roundness, are counted. This method of shape based filtering is employed to filter out the tracks that are elongated. These elongated tracks may be present due to the scratches and other damages that occur on the CR-39 detector during the etching process and are not considered for counting. In addition to these, CR-39 detector exhibit inherent background track due to imperfections, micro voids, micro cavities, air entrapments and ambient environmental radiations. The lower and upper limits of diameter and roundness factor of acceptable tracks are 60 & 250 μm and 0.7 & 2.0, respectively.

The upgraded image analysis system has improved the efficiency of the dose evaluation process. This includes minimum detection limit (MDL), sensitivity (no of tracks/mSv), faster counting and dose linearity. These improvements have been possible due to (i) improved image resolution, (ii) increased range of acceptance criterion in terms of diameter and roundness factor of tracks (which counts some of the tracks otherwise not considered for counting), and (iii) use of advanced computer.

Fig. 6: Photograph of image analysis system

Control Detector (Back ground)	CR-39 detector exposed to 2mSv
	

Fig. 7: Image of tracks on CR-39 detector after ECE processing as seen through image analysis system.

7.4 Chemical Etching (CE) Technique:

Earlier, all the exposed CR-39 detectors were processed only by ECE technique. However, in a situation where the neutron dose is suspected to be in excess of 10 mSv, ECE can not be used due to higher track density which could not be counted by image analyzer. In such situation, chemical etching (CE) method has been developed[16]. This technique was introduced in 2007 for evaluation of doses above 10mSv and standardized. As CE technique is applicable for high neutron dose measurement, the optimization has been carried out with detectors exposed to doses above 10 mSv. For the purpose of optimization, the dose equivalent delivered was 20 mSv from ^{241}Am-Be neutron source. The duration for chemical etching at 60°C was varied from 6 to 9 h in steps of 1 h. Subsequent to etching, the chemically etched detectors are washed thoroughly by water and dried and later counted under microscope with 20x magnification. It is observed, from Table 1 that as the etching duration increases, the background reduces, but after certain duration, further etching reduces the signal tracks also. Considering the net counts (tracks cm^{-2}) and ratio of signal (net tracks cm^{-2} corresponds to 20 mSv) to noise (number of tracks cm^{-2} corresponds to un-irradiated detector), it was found that etching duration of 7 h is optimum[17]. The CR-39 detectors are therefore, subjected to optimized chemical etching in 7 N KOH solution at 60°C for 7 h.

In personnel monitoring, if it is found that the neutron dose equivalent is of the order of 10 mSv, non-etched part of the CR-39 detector is cut and etched further using optimized CE technique mentioned above. Subsequently the processed detectors are counted by an optical microscope for dose evaluation.

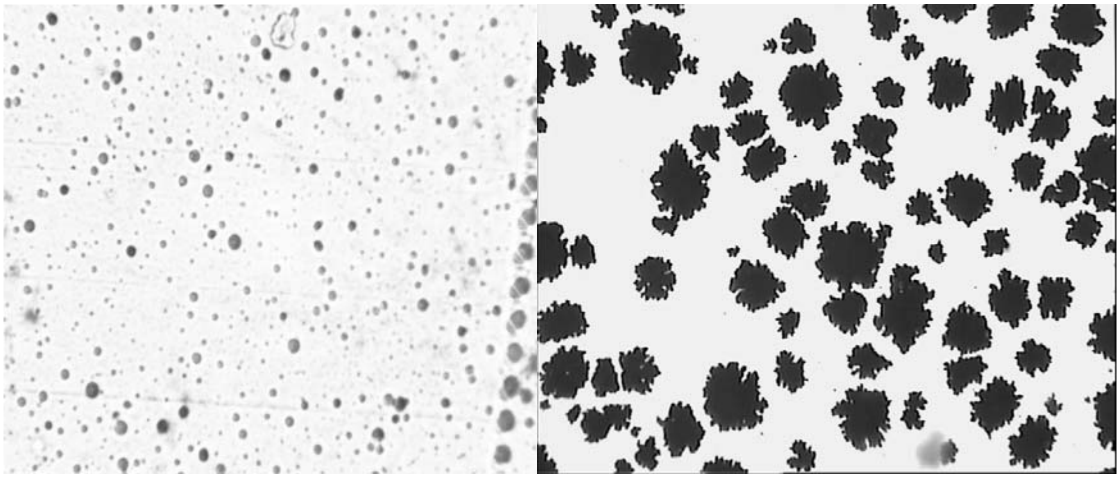
TABLE 1. Results on the optimization of the chemical etching.

Etching duration (h)	Control (tracks cm^{-2})	Gross Counts (tracks cm^{-2})	Net counts (tracks cm^{-2})	Signal/Noise ratio
6	1145	8350	7205	6.3
7	485	10060	9575	19.7
8	250	4290	4040	16.1
9	60	3860	3800	63.3

Note: Dose equivalent delivered was 20mSv.7N KOH was used as chemical etchant at 60℃.

7.5 Track counting for CE Technique

The tracks etched by chemical etching method are counted using a high magnification (20x magnification) optical microscope. With this magnification, the counting field of area $0.005 cm^2$ of the detector can be covered. The diameters of the etched tracks produced by recoiled proton are in the range of 3-10 μm. Tracks are counted manually for 50 different fields around the center of the detector. This process of counting is followed for both un-irradiated and irradiated detector and used for the assessment of track density. The tracks appeared as dark spots on a clear white background when viewed through the microscope and is shown in Fig.8 (A). However, if the detector is etched by ECE technique and viewed through the microscope with 5x magnification it appears as florets in 2D and is shown in Fig.8 (B).



A. CE tracks seen through microscope B. ECE tracks seen through microscope.

Fig. 8 Image of etched tracks seen under microscope

8. CALIBRATION PROCESS IN TERMS OF PERSONAL DOSE EQUIVALENT Hp(10)

A reproducible and reliable measurement of neutron dose depends on the soundness of the calibration procedure. International Commission on Radiation Units and Measurements (ICRU), in its publication 39 (1985), has introduced operational quantity called personal dose equivalent, Hp(10), for personnel monitoring[18]. Hp(10) is defined as dose equivalent in soft tissue at a depth of 10 mm below a specified point on the body or a phantom having composition of ICRU tissue with density 1 $gm.cc^{-1}$. The procedure for calibration of neutron personal dosemeters in terms of Hp(10), has been described in ISO standards 8529-2, 1998[19]. In our laboratory, the calibration of CR-39 dosemeter is carried out as per the ISO recommendations.

For this purpose, irradiation of CR-39 dosemeter, is carried out in a low scatter laboratory on an ISO water slab phantom. The phantom has outer dimensions 30 cm x 30cm x 15 cm with the walls made of PMMA. The thickness of the front wall is 2.5 mm and all other walls are of thickness 10 mm. The personnel dosimeters are fixed on the front face of the phantom within an area of 10 x10 cm around the centre as shown in Fig.9. When the ISO water slab phantom is used as described above, no corrections are applied to the reading of the dosimeter under calibration due to the differences in backscatter between this phantom and the ICRU tissue slab phantom.

The reference conditions used for calibration irradiation are

(i) Neutron energy spectra of ^{241}Am-Be: average energy : 4.4 MeV and yield : 2.5 x 10^6 n/sec

(ii) Angle of radiation incidence: Normal incidence

(iii) Distance between detector and source : 75 cm

Fig. 9: Irradiation set-up of neutron badges for calibration.

The calibration factor N_B (mSv-cm^2 tracks^{-1}) for the dosimeter under calibration is obtained from the following relation:

$$N_B = \frac{\Phi h_\phi}{M_B} \quad \text{---------------------------} \ (3)$$

Where M_B is the measured net tracks cm^{-2} mSv^{-1} and the neutron fluence (ϕ) in terms of n/cm^2 at 75 cm (for Am-Be source, ϕ = 2.44E+06 n/cm^2 for 1mSv dose equivalent.)

The conventional true value of the measured dose equivalent Hp(10) is determined from the fluence and the appropriate fluence to dose equivalent conversion coefficient (h_Φ) expressed in pSv-cm^2. For reference conditions, the dose equivalent response of the dosemeter (tracks cm^{-2} mSv^{-1}) is obtained from the relation: $R \approx \frac{M_B}{\Phi h_\Phi}$ The calibration factor is determined as the reciprocal of response factor. The typical calibration factor for CR-39 using ECE technique for ^{241}Am-Be spectra is 0.0058 mSv-cm^2 tracks $^{-1}$. Whereas that using CE technique for ^{241}Am-Be neutron spectra is 0.0016 mSv-cm^2 tracks $^{-1}$. Typical calibration factor for ^{252}Cf using ECE technique is 0.0045 mSv-cm^2 tracks $^{-1}$.

9. PERFORMANCE CHARACTERISTICS OF CR-39 DETECTORS FOR USE IN NEUTRON PERSONNEL MONITORING.

9.1. Minimum detection Limit (MDL) and sensitivity of CR-39 detector

The minimum detectable dose in mSv for CR-39 based dosimetric system, is the defined as the dose equivalent level at which reading is significantly greater than the background. It is given by equation 4.

$$\text{MDL} = N_B \times 3\sigma \quad \text{--------------------(4)}$$

Where N_B is the calibration factor for CR-39 detector as defined in equation 3 and σ (tracks cm^{-2}) is the standard deviation of the background counts (number of tracks cm^{-2} of un-irradiated detectors) obtained from the average of the 20 un-irradiated and processed detectors. Sensitivity is defined as the number of tracks cm^{-2} mSv^{-1} for a particular radiation. For estimation of minimum detectable dose and sensitivity of CR-39 detectors using both ECE & CE techniques, 20 CR-39 detectors with radiator were irradiated to 1 mSv dose equivalent of ^{241}Am-Be neutron source. The irradiation was carried out at 50 cm from the source under low scatter conditions in air. All the irradiated detectors along with an equal number of un-irradiated detectors (served as control detectors) were etched using ECE and CE techniques under optimized conditions.

The values of background count and MDL determined by ECE and CE techniques are given in Table 2. It was found that the values of MDL using ECE and CE techniques are 0.10 and 0.27 mSv, respectively. In practice, ECE technique is used for processing neutron personnel monitoring dosemeter, when neutron dose equivalent is below 10 mSv, whereas CE technique is used when it is beyond 10 mSv.

TABLE 2: MDL and sensitivity of CR-39 detectors using ECE and CE techniques**.**

Etching Technique	Control (tracks cm^{-2})	Gross counts* (tracks cm^{-2} mSv^{-1})	Net counts (tracks cm^{-2} mSv^{-1})	MDL (mSv)
ECE	26 ± 6.5	212± 4.5	186 ±7.4	0.10
CE	485 ± 93	1529 ±85	1044 ± 125	0.27

**The CR-39 detectors were irradiated to 1mSv neutron dose equivalent of ^{241}Am-Be on phantom.*

In practice, most of the sheets of CR-39 (procured from the manufacturer) of a single batch have a MDL value comparable to that of the sample sheets. However, in some of the sheets, the MDL could be higher than that of the sample sheets. This could lead to the reporting of false positive doses. To avoid reporting of false positive dose, the MDL value for reporting doses during personnel monitoring service was considered to be ≥ 0.20 mSv.

Further, as per ICRP recommendation, recording level (R) for individual monitoring should be derived from the duration of the monitoring period and an annual effective dose of no lower than a value of 1 mSv or an annual equivalent dose of 10% of the relevant dose limit. Doses below the recording level will not be included in the assessments of a workers dose, indicating that an absolute uncertainty in terms of dose given by the following relation is acceptable.

$$R = \frac{1\ \text{mSv x Monitoring period in months (3 months)}}{12} \quad \text{-------------------(5)}$$

Based on this relation, for individual monitoring for radiation workers in neutron field, the value of acceptable recording level is 0.25 mSv which is above our reporting level.

Sensitivity of the CR-39 detector depends on the radiator, etching conditions used, thickness of the detector, shape & size criteria used to identify tracks in image analysis system. Hence changing any one of the above parameters can affect the sensitivity of CR-39 detector. The sensitivity of CR-39 using ECE and CE are found to be 186±7.4 and 1044 ± 125 cm^{-2} mSv^{-1}, respectively as presented in Table 2. It may be noted, that though the number of neutron induced proton tracks are same in the CR-39 initially, the number of tracks finally revealed depends on the etching technique. In case of ECE, with the application of electric field, 3-4 neighboring tracks are merged to reveal a single track at low magnification (2X). Whereas for CE, the merging of tracks does not occur, so tracks revealed are more in number. Hence the sensitivity in CE technique (1044 tracks cm^{-2} mSv^{-1}) is always higher than ECE technique (186 tracks cm^{-2} mSv^{-1}).

9.2 Linearity of dose response of CR-39

Dose response of CR-39 detector was studied using two etching techniques. For this purpose, for each dose equivalent, 9 dosimeters (comprising of a detector with radiator in front) were irradiated on ISO water phantom. The delivered dose equivalents were 1, 2, 3, 5 and 10 mSv for ECE technique and 10, 20 30, 40, 50 and 60 mSv for CE technique. The irradiations conditions were same, as stated in section 8. The irradiated detectors along with equal number of control detectors were processed with (i) optimized ECE and (ii) optimized CE techniques stated in section 7.1 and 7.4 and counted using the corresponding imaging systems for establishing the dose response of the CR-39 using these techniques [20]. Number of tracks cm^{-2} versus delivered dose equivalent Hp(10) was plotted for both the etching techniques and shown in Fig. 10 and 11. For dose range up to 5 mSv, it was found that the dose response is linear within ± 7% and whereas beyond this range (upto 10 mSv) the linearity in dose response is within ±19%. In practice, it has been observed that 99% of the 2100 radiation workers receive dose equivalent up to 5 mSv, hence evaluation of neutron dose in this range is accurate within ± 7%. Beyond the dose equivalent of 10 mSv the track density becomes too high to count with ECE method. In such case CE technique is used. The dose linearity using CE technique in the dose range 10-60 mSv is found to be ± 18%.

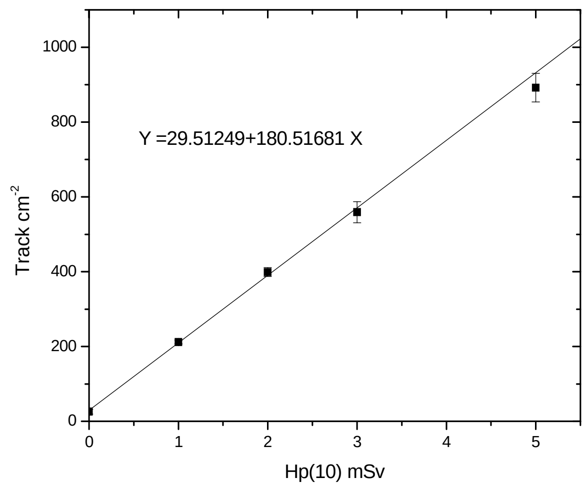


Fig. 10: Dose linearity of CR-39 using ECE technique in the dose equivalent range 1-5 mSv for ^{241}Am-Be fast neutrons. Calibration factor = 0.0058 mSv-cm^2 tracks $^{-1}$

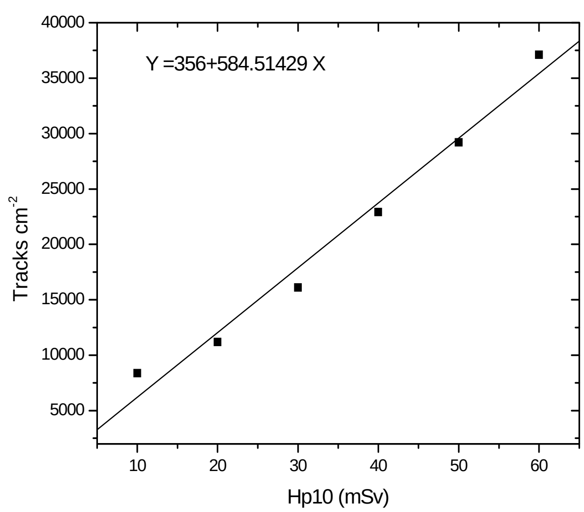


Fig.11: Dose linearity of CR-39 using CE technique in the dose equivalent range 10-60 mSv for ^{241} Am-Be fast neutrons. Calibration factor = 0.0016 mSv-cm^2 tracks $^{-1}$

9.3 Energy response of CR-39

Energy response of CR-39 detector is defined as the variation in the no of tracks cm^{-2} mSv^{-1} with neutron energy. For studying the energy response, 10 sets each, (comprising of a CR-39 detector with radiator in front) were irradiated on phantom to different fast neutron spectra from ^{241}Am-Li, ^{252}Cf-D_2O ,^{241} Am-F ,^{252}Cf , ^{241}Am-B, ^{241} Am-Be and ^{239}Pu-Be. The fluence averaged energy of ^{241}Am-Li, ^{252}Cf-D_2O, ^{241} Am-F, ^{252}Cf , ^{241}Am-B, ^{241} Am-Be and ^{239}Pu-Be are 0.45 ,0.5, 1.6, 2.1, 2.6, 4.4 and 4.5 MeV, respectively. The dose equivalent delivered for the energy response was 1 mSv at a distance of 75 cm from the source. All the neutron sources are standardized separately to get the exact neutron yield at RSSD, BARC. For each energy point, a set of 10 detectors were irradiated and processed further using (i) optimised ECE and (ii) optimized CE techniques. Subsequently the detectors were analyzed by the corresponding imaging systems of ECE and CE process.

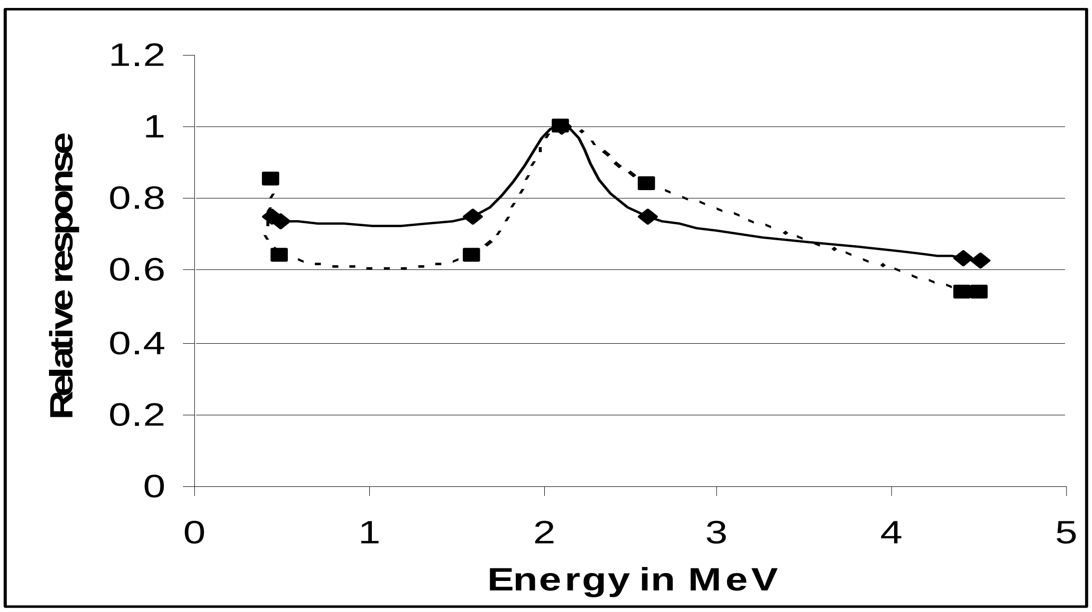


Fig. 12: Energy Response of CR-39 in ECE and CE Techniques normalized to ^{252}Cf spectra. (Solid line -ECE technique ; Dotted line- CE technique)

The response of the detector (net average tracks cm^{-2} mSv^{-1}) was evaluated for all these sources and represented in Fig.12. The energy response for CR-39 is normalized with respect to bare ^{252}Cf is within 35% when ECE technique is used. Whereas it is within 45% if CE technique is used. The variation in the energy response of CR-39 is attributed to the fact that response of the detector is optimized for ^{252} Cf source (2.2 MeV) with 1 mm polythene radiator. Hence, during personnel monitoring, appropriate correction factor is applied to take care of the energy response in the higher energy range for dose evaluation. In case of reactors, where fission spectrum is expected, calibration factor generated based on irradiation of bare ^{252}Cf is used. In case of accelerators, where high energy neutrons are expected, ^{241}Am-Be derived calibration factor is used.

9.4. Angular response of CR-39

One of the test parameter of personal dosemeter is it's angular response to radiation. CR-39 track etched planar detectors show a strong angular dependence as charged particles are recorded only if the angle of radiation incidence with respect to normal is more than the critical angle of registration[21]. Critical angle of registration (θ_c) is defined as the angle below which tracks cannot be recorded as they are removed by the chemical action of the etchant. The critical angle depends on the detector material, the etching conditions, the type of charged particle, and varies significantly with particle energy [22]. As a consequence, the registration efficiency of neutrons in the CR-39 detector used for neutron personnel monitoring is strongly influenced by the direction of radiation incidence [23].

It can be seen from Section 6, Fig.2 that for tracks incident on the surface, the component of V_T perpendicular to surface, $V_T \sin \theta$ must exceed V_B, in order to produce a track.

$$V_T \sin \theta > V_B$$

Critical angle (θc) is given by the following equation

$$\theta c = \sin^{-1} V_B/V_T \text{------------------------------------}(6)$$

where V_B is the bulk etching rate, and V_T is the track etching rate.

For oblique tracks to register, the incident angle should be greater then the critical angle for registration. If incident angle is less then critical angle, the track is removed ($V_B > V_T$). It also varies with the etching conditions such as applied voltage, temperature and duration of etching.

For the determination of angular response, sets of 10 dosimeters each along with 1 mm radiator in front were irradiated free in air and on phantom separately to 1 mSv of neutron dose equivalent of ^{241}Am-Be and ^{252}Cf spectra. The neutron dose equivalent delivered was calculated by applying the neutron fluence to dose conversion coefficients $H^*_{\Phi}(10)$ for air and $H_{p\Phi}(10)$ for phantom in ^{241}Am-Be spectra and ^{252}Cf spectra (ISO 8529-3,1998). The dosemeters were irradiated by varying angles in multiples of 15° in the angular range from 0°-90°. Irradiation on phantom was carried using an ISO water slab phantom as shown in Fig. 9. The variation of angle of incidence was achieved by rotating the platform on which the phantom was placed around the vertical axis which passes through the point of test.

Table 3. Comparison of the response of CR-39 to neutrons at different incident angles in air and on phantom along with conversion co-efficient $H_{p,slab\Phi}(10,\alpha)$.

Angle of incidence	Response in air (tracks cm^{-2})	Normalised response (in air)	Response on phantom (tracks cm^{-2})	Normalised response (on phantom)
0º	259 ± 30	1.00	267± 35	1.00
15º	267 ± 25	1.03	280± 30	1.05
30º	194 ± 20	0.75	176± 16	0.66
45º	213 ± 18	0.82	205± 12	0.77
60º	146 ± 15	0.56	130± 15	0.49
75º	90.5 ± 10	0.35	94 ±15	0.35
90º	63.5 ± 9	0.25	58± 10	0.22

Note: Fluence to personal dose equivalent conversion coefficient $h_{p,slab\Phi}(10,\alpha)$ for ^{241}Am-Be spectra taken from ISO standards ISO 8529-3,1998 .

The angular response of CR-39 detector in terms of tracks cm^{-2} to ^{241}Am-Be spectra in free air and on ISO phantom is presented in Table-3. The relative response of CR-39 with varying angles for ^{241}Am-Be neutron source spectra in free air and on ISO phantom is shown in Fig.13. It is observed that as the angle of incidence of the neutron normal to dosimeter approaches 90º, the response drops rapidly. This is attributed to the fact that with increasing angle, recoil protons enter almost parallel to the surface of the dosimeter having incident angles within the critical angle and hence not registered as these low depth (angular) tracks are removed by the etching process. The angular dependence of the dosimeter, in air and phantom is nearly the same indicating that phantom does not influence much to the angular response of CR-39. These observations are in good agreement with the data available in literature [24].

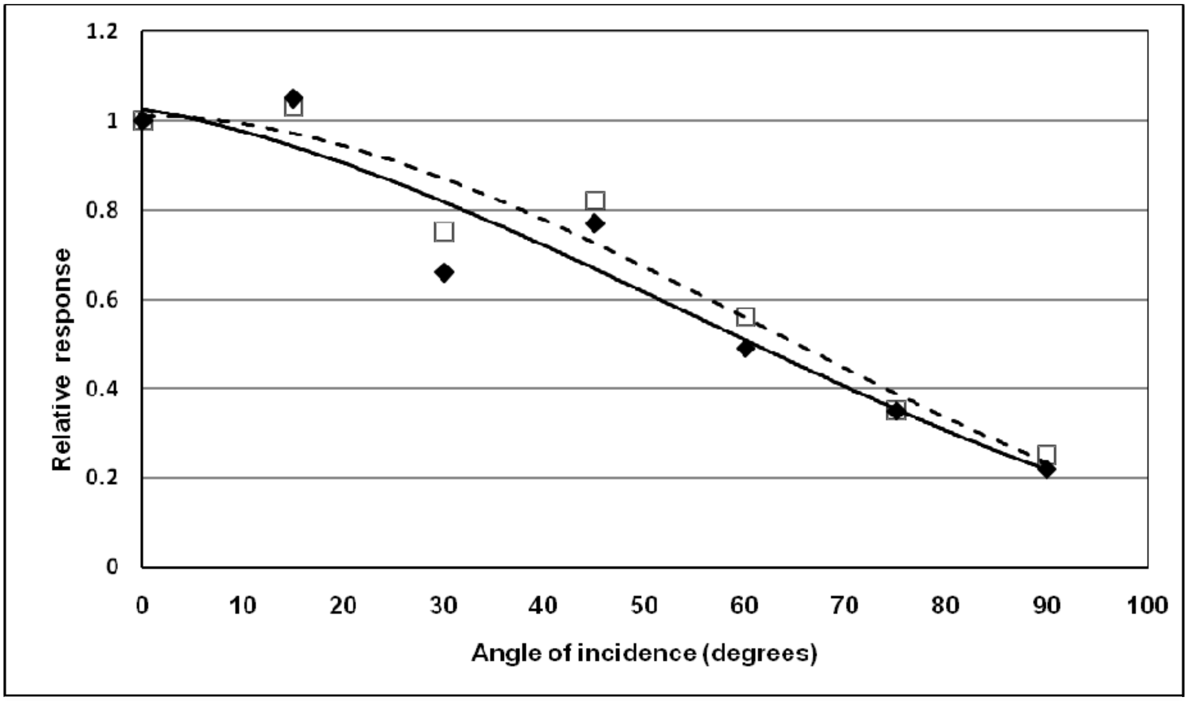


Fig.13: Relative response of H'(10,α)/H*(10) in free air (*dashed line*), Hp(10,α)/Hp(10,0º) on phantom (*solid line*).

The normalized response of CR-39 at various angles of incidence for two different source spectra ^{252}Cf and ^{241}Am-Be are presented in Fig 14. For ECE technique, it can be seen that for angles upto 45º the normalized response (with respect to 0 º) is the same in both the neutron energies with 20% reduction in the response. However, at 90º, the relative response drops to 0.25 for ^{241} Am-Be neutron spectra (4.5 MeV) whereas for ^{252}Cf spectra (2.1 MeV) it drops to 0.16. Hence, it is inferred that the angular dependence reduces with increasing neutron energies. As per ISO standards on performance and test requirements of passive neutron dosimeters, the arithmetic mean of the response of a dosimeter at angles of incidence of 0º, 15º, 30º, 45º and 60º from normal should not differ by more than 40% from the response at normal incidence. The average angular dependence of CR-39 detector upto 60 º differs by about 20% with respect to the normal incidence and is within the limits recommended by ISO.

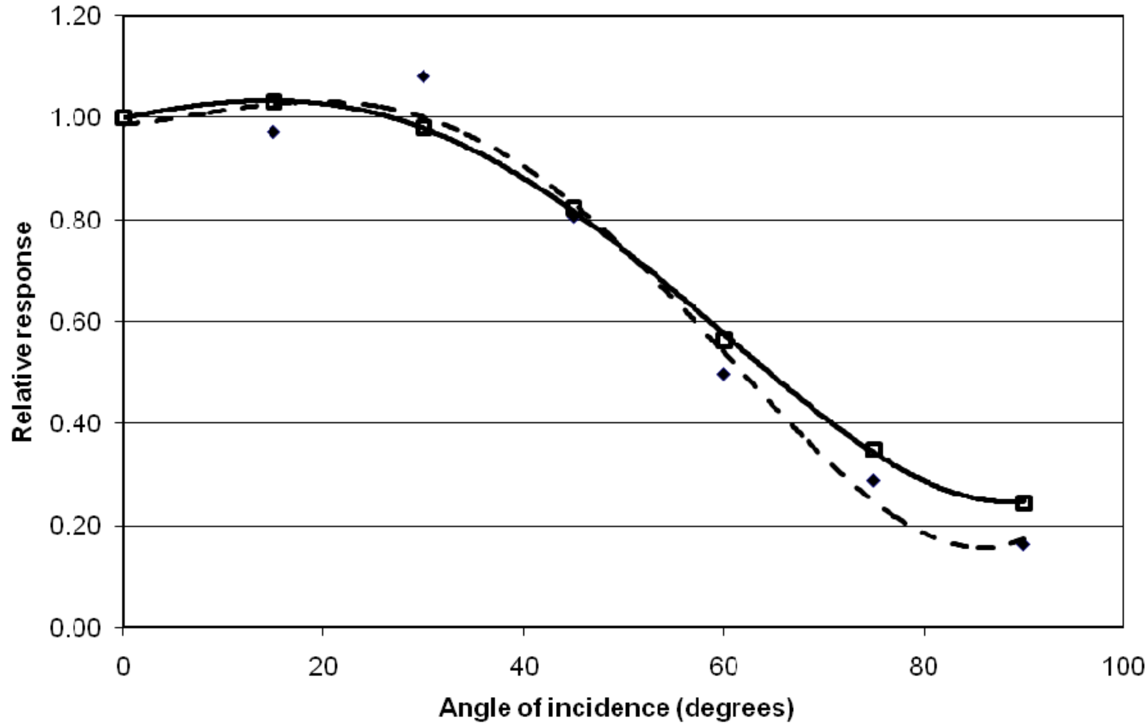


Fig.14: Directional dependence CR-39 dosimeter for ^{252}Cf (*dashed line*) and ^{241}Am-Be (*solid line*) spectra processed by ECE Technique. The response is normalized to 0º *(normal incidence of neutrons to detector surface).*

9.5 ISO performance requirement for solid state nuclear track detector (ISO 21909:2005(E)

ISO has specified the requirement of performance criteria for personnel neutron dosemeter. The status of the performance of the CR-39 based neutron dosemeter as per ISO performance tests is presented in Table-4.

Table 4: Performance status of CR-39 based neutron dosemeter.

No.	**Performance characteristics**	**Performance requirement**	**Performance status of neutron dosemeter.**
1.	linearity	The response to neutrons shall not vary by more than 10% over the personal dose equivalent range	For dose range upto 5 mSv, the dose response is linear within ± 7%.
2	Detection threshold	The detection threshold shall not exceed 0.3mSv	The detection threshold for our dosemeter is 0.2mSv.
3	Fading	The response of dosemeters irradiated at the beginning of a storage period shall not vary by more than 30% for a 90-day storage period under standard test conditions.	The dosemeter response is within ± 5%.
4	Ageing	The response of dosemeters irradiated at the end of a storage period shall not vary by more than 30% for a 90-day storage period under standard test conditions.	The dosemeter response is within ± 25%.
5.	Effect of light exposure	The zero point shall not change by more than 1mSv when exposed to a xenon lamp equivalent to bright sunlight (295nm to 769 nm) to 1000W/m^2 for one day.	For one week exposure, the reading of dosemeter is within ± 10 %.

		For exposure for one week, the reading shall not differ from the reading of a dosimeter kept in dark by more than 10 %.	
6	Energy response	The response at normal incidence in the 0.5 – 4.4 MeV energy (fluence weighted average energy) range for the dosimetry system shall not vary by more than ±50 % for a personal dose equivalent of at least 1mSv.	The normalized energy response of our dosemeter with respect to bare ^{252}Cf is within 35% when ECE technique is used.
7	Angle dependence of response	The arithmetic mean of the response of a dosemeter at angles of incidence of 0º, 15º, 30º, 45º and 60º from normal shall not differ by more than 40% from the response at normal incidence. The personal equivalent should be at least 1mSv.	The average angular dependence of our detector upto 60º differs by about 20% with respect to the normal incidence.

10. DATABASE MANAGEMENT SYSTEM FOR NEUTRON DOSE RECORDS

Database management software is in operation at our laboratory for maintenance of dose records of radiation workers. It is used for the purpose of evaluation of dose, making dose reports, letters to institutions and storing dose records. The current software has been upgraded from dbase to VB 6.0 and uses MS Access Database at the backend. Presently it maintains records of 2100 radiation workers enlisted in neutron personnel monitoring service. It has database search options for radiation worker, institution details, personal no etc. It also creates annual and quarterly dose reports in special batch format required by NODRS (National Occupational Dose Registry System). In addition to above, it has some more useful utilities such as creating Frank Numbers for postal registration etc.

11. FUTURE DEVELOPMENT IN NEUTRON PERSONNEL MONITORING.

One of the desirable characteristics of a personnel dosimeter is to achieve lower MDL (about 0.1mSv with 3σ) and higher sensitivity. To achieve this, quality control on every aspect of processing of dosemeter is required. The main hurdle in achieving this is the quality of CR-39 sheets. The sheets should be polymerised with minimum manufacturing defects (background signal) and uniformity in thickness of the film should be maintained. The sheets are expensive and imported. In view of this, we have undertaken an MoU programme for indigenous develoment of CR-39 films in collaboration with Goa University. If successful, it will help in maintaining quality control during polymerisation resulting in the reduction of background signal leading to lowering the MDL of the dosemeter.

The threshold energy of CR-39 detector is 100 keV. In the lower energy, the threshold can be furthur lowered using borane doped CR-39 (carborane), using lithium borate convertors in conjunction with CR-39 detectors to detect the thermal and intermediate neutrons. Alternatively, lithium based TLDs based on ^{6}LiF can be used along with CR-39 to cover the entire energy range thermal to fast neutrons and can be used in neutron monitoring. Development of a neutron badge based on CR-39 and neutron sensitive TLD (to cover lower energy) is under progress.

Neutron dose is evaluated presently using the calibration factor generated by irradiating neutron dosemeter to ^{241}Am-Be and ^{252}Cf. However, the neutron spectrum at the site may differ considerably from the neutron spectrum of the above two sources. Hence to enhance the accuracy in the dose evaluation process it is planned to use site specific calibration factor during dose evaluation. The spectrum can be generated using multipurpose neutron spectrometers having the provision to measure neutron spectrum and corresponding ambient dose equivalent (mSv) in the radiation environment at the site.

With new reactors and accelerators coming up in the country, the number of radiation workers in the neutron field is likely to increase in future. To cater to the increasing need, faster processing and track counting method of the detector needs to be developed and established. It is planned to explore the faster processing such as use of microwave based etching and automated image analyzer with a facility to count multiple detector at a time.

12. SUMMARY

The report summarizes the development taken place in neutron personnel monitoring in the dose evaluation process, instruments, software and calibration procedures.

These include

- Establishment of chemical etching technique for evaluation of neutron dose equivalent greater than 10 mSv.
- Up-gradation of image analysis system required for track counting made the dose evaluation faster and lowered the minimum detectable dose.
- Introduction of batch wise performance characteristics of CR-39 detector as a part of quality assurance procedures.
- Introduction of laser cutting of CR-39 sheet has reduced the overall time required for the preparation of the neutron badge before dispatch.
- Data base management software has been upgraded for calculation of dose, maintenance of dose record and preparation of dose reports. Up-gradation of this software has reduced the overall dose evaluation time to a significant extent.

13. ACKNOWLEDGEMENTS

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