Neutron dosimetry

Francesco d'Errico

Yale University, School of Medicine, New Haven CT 06510, USA, and
Università di Pisa, Dipartimento di Ingegneria Meccanica, Nucleare e della Produzione, I-56126 Pisa, Italy
francesco.derrico@yale.edu

1. Introduction

These notes review the status and the developments in the field of neutron dosimetry with solid state techniques. The review focuses on nuclear track emulsions, thermoluminescence dosemeters, etched-track detectors, superheated emulsions and direct ion storage chambers which are the subject of recent standards and documents issued by ANSI (2000), ICRU (2001) and ISO (2005) In addition to these official publications, some of the main sources of this review are the proceedings of some recent conferences on Solid State Dosimetry and on Nuclear Tracks in Solids.

Personnel occupationally exposed to neutrons continue to represent a small fraction of the radiation workers. The economic implications of this fact, together with the complexity of neutron detection physics, are behind the relatively slow evolution of personal neutron dosimetry systems. Although they have not made quantum leaps, neutron dosimetry techniques have however improved significantly in response to a combination of regulatory and technical challenges emerged in the past decade. At the regulatory level, in 1996 the Council of the European Union issued the directive 96/29/EURATOM (EC 1996), requiring EU member states to adopt basic safety standards based on ICRP 60 and also requiring the assessment of significant increase in exposure due to natural radiation sources, including cosmic radiation. In 1996, ICRU and ICRP jointly issued the long awaited official conversion coefficients for the operational dose equivalent quantities, allowing full implementation of the 1990 Recommendations of the ICRP (1991). Accuracy requirements on the measurements were indicated by the ICRP (1997). For the USA, the requirements for the selection, use and calibration of personal neutron dosimetry systems were published by ANSI in the American National Standard N13.52, issued in 2000. In 2001, the ICRU issued Report 66 providing guidance for the measurement of the operational dose equivalent quantities for neutrons and indicating the performance that can be expected of a variety of neutron dosimetry systems. Finally, following the 8529 series of standards on reference neutron radiations, issued between 1998 and 2001, ISO issued a standard on performance and test requirements for passive personal dosimetry systems.

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This material is derived from the literature indicated above and it is meant for educational purposes only.

2. Nuclear Track Emulsions

Photographic emulsions consist of microscopic crystals (grains) of a silver halide, usually silver bromide, dispersed in a gelatin layer. The grain size ranges from typically 0.2 μm in nuclear emulsions up to 2 μm in some radiology films. Emulsions are applied as a thin layer on one or both sides of a cellulose acetate or polyester film, or for some research applications, on glass plates. For a grain to be developable, a number of silver ions must be reduced to elemental silver by the passage through the grain of a proton or heavier charged particle, or secondary electrons. Photographic development is the process of amplification in which a few silver atoms present in developable grains are increased in number by a factor

of 10^7 or more, converting the whole grains to elemental silver and making them visible under a microscope. The reduction process is enhanced by the presence of sensitizers in the grain, for example iodine and sulfur. More information on the fundamental aspects of the photographic process may be found in Powell et al. (1959), Mees (1954), Dudley (1966) and Gurney and Mott (1938).

Emulsions can be prepared with a range of properties. Fine grained nuclear emulsions have been and, to a limited extent, are still used for the identification of charged particles, for neutron spectrometry, and for the study of the interactions of particles. Neutron energy distribution information can be derived from an analysis of the proton track length distribution. For routine neutron personal monitoring, only one type of nuclear emulsion is commercially available, and in regular use, the Kodak Nuclear Track emulsion type A (NTA). NTA film consists of fine grains of silver bromide, of mean diameter about 0.2 μm, suspended in a gelatin matrix. The gelatin is mainly hydrated collagen. The degree of hydration of the collagen, and therefore the hydrogen composition, depend upon ambient temperature and humidity. The emulsion, which has a thin, 0.5 mm, protective layer, is between 25 and 35 mm thick, is coated onto one side of a cellulose triacetate film base and is wrapped in various layers of paper. About 100 ionizations within a grain are necessary to render it developable, that is the deposition of at least 1 keV in the 0.2 mm diameter grain.

NTA is relatively insensitive to photons and electrons. Neutrons interact via the $^{14}N(n,p)^{14}C$ reaction (nitrogen is present in the gelatin), and by elastic scattering on the hydrogen (also, contained in gelatin), in the cellulose triacetate base, the paper wrapping and the dosimeter holder. At neutron energies above about 20 MeV, tracks produced by recoil nuclei and resulting from non-elastic interactions including 'stars' become important (see Dudley (1966) or Lehman (1961) for more details). Dependent somewhat on the construction of the dosimeter holder, the personal dose equivalent response to thermal neutrons of an NTA detector is similar to its fast neutron response. The fast neutron response has a lower energy limit of about 0.5 MeV; a proton energy of 0.3 to 0.4 MeV corresponds to a 4-grain track.

The measurement of thermal neutrons by means of a converter element, normally by the (n, γ) reaction on cadmium, and a photon/electron sensitive photographic film has been in widespread use. In recent years this method has been all but abandoned for the determination of thermal-neutron dose equivalent. Thermal neutron capture by cadmium leads to the emission of a cascade of photons of total energy of about 9 MeV. Thin foils of cadmium (about 1 mm) placed at either side of the film can be part of a multi-filter film badge (see, for example, Iles et al. (1990)) and may serve as a flag detector for thermal neutrons. After development, the optical densities under different filters are read by means of a densitometer and the density beneath the cadmium filter related via a calibration factor to the thermal neutron exposure, after subtraction of the photon reading.

The energy dependence of response of NTA is shown in Figure 1 [data from Drew and Thomas (1998) and Bartlett et al. (1980) supplemented by calculations by Tanner et al. (2000)]. The dosimeter response characteristics are determined in part by the design of the dosimeter holder, and the processing and read-out method. The thermal and epithermal response can be modified by the use of thermal neutron absorbing material. The fast-neutron threshold is influenced by the photographic development procedure, the read-out magnification and the method of reading - whether assisted by an image analysis system or not. Protons of energy greater than 4 MeV can penetrate the paper wrapping and therefore for neutrons of energies greater than this value, the dosimeter response is influenced by the material of any encapsulation. The recognition of a proton track becomes more difficult at proton energies greater than about 10 MeV, because of the wide separation of grains along the path of the sparsely ionizing proton. However the spallation cross-section increases and the response of the detector becomes determined by the tracks of spallation products. There are also stars - spallation reactions of the emulsion constituents.

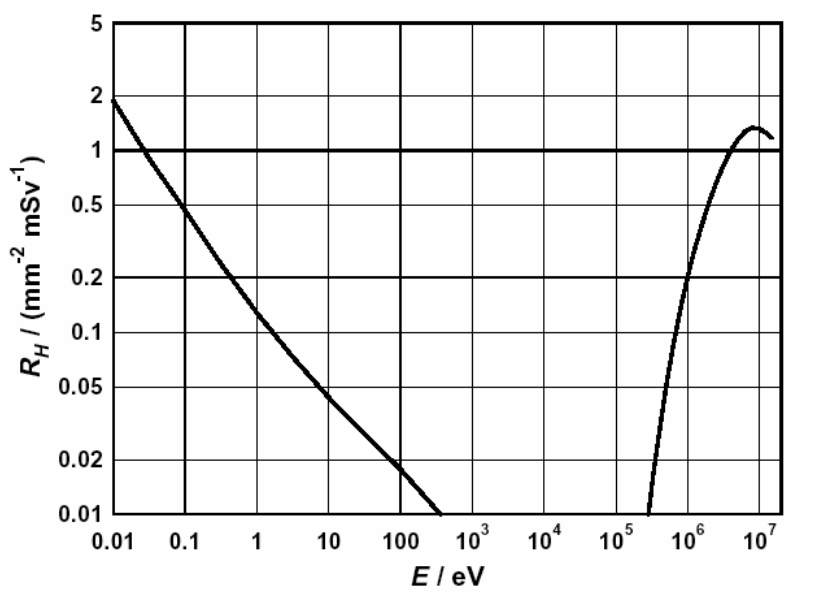

Figure 1: *Personal dose-equivalent response, R_H, (with respect to $H_p(10)$) as a function of the energy, E, of incident neutrons, normalized to unity for Am-Be neutrons, of an NTA-film dosimeter for frontal irradiation (after Drew and Thomas (1998) and Bartlett et al. (1980)).*

The angle dependence of response varies with neutron energy. For thermal energies, the fluence response is approximately isotropic. For fast neutrons, the angle dependence is complex, depending, as for the energy dependence, on a combination of parameters: the kinematics of proton generation and absorption in detector and covering materials and encapsulation; development procedures; and the read-out method. For irradiations from the forward half-space the response with respect to $H_p(10)$ deviates by about 20 % from that for normal incidence (Bartlett et al., 1980).

The critical level (reading or corresponding dose that is indistinguishable from background with a certain probability) and detection limit (dose that is distinguishable from background with a certain probability level) for a given incident neutron energy depend on the average background track density and its statistical distribution, and the dosimeter sensitivity including the area read. Typical numbers of tracks are 2 mm^{-2} background (approximately Poisson-distributed) and 20 mSv^{-1}mm^{-2} for ^{241}Am-Be-source neutrons, giving a critical level of 150 mSv and a detection limit (with 95% confidence) of 360 mSv.

The latent image is susceptible to fading. Fading results from the oxidation of the silver atoms in the developable grains, by the combined action of oxygen and moisture (Albouy and Faraggi, 1949; Liede, 1962). To a large extent, this can be prevented by first partially desiccating, and then sealing, the emulsion pack in an aluminium/paper-laminate moisture-proof pouch. Both these procedures need to be carried out in a dry nitrogen atmosphere (Portal, 1970). The sealed emulsions may then be used in normal laboratory conditions (Bartlett and Creasey, 1977) and even in hot and humid conditions (Creasey and Bartlett, 1978) for wearing periods of 12 weeks and more.

Nuclear emulsion dosimeters have been successfully used in the non-nuclear industry and in research institutes. In general, the energy dependence of the response and photon sensitivity of the detector militate against its use in workplaces where there is a degraded fission energy distribution accompanied by photon radiation. However, for the neutron fields from bare or lightly-shielded radionuclide sources or particle accelerators, and in workplaces around high-energy particle accelerators, nuclear emulsion neutron personal dosimeters can be effective and reliable, subject to efficient desiccation and sealing, with good angle dependence of response.

The emulsions are relatively inexpensive; however, track analysis under a high-magnification microscope is laborious. For this reason, recent research on nuclear track emulsions has focused on the development of automated track scanning methods. Track

identification algorithms are inevitably complex, a study from CERN (Müller and Otto, 1999) reports that each detector-field of 0.07 mm^2 may contain more than a thousand objects which have to be analysed in terms of shape, area, convexity, etc., in order to identify the recoil proton tracks. A prototype automated system has been reported to present a linear behaviour for doses up to several mSv, however, the track identification rate is about 30% lower than the values from a trained human operator. Overall, these are encouraging developments towards the implementation of automated systems in personal dosimetry services, where they would not only expedite detector processing but also eliminate the risk of human evaluation inconsistencies.

3. Thermoluminescent Detectors

With the demise of nuclear track emulsions, thermoluminescence detectors (TLD) have gained popularity thanks to a number of attractive properties such as low cost, simplicity, convenient automated reading, durability, linearity of response and low detection limit. TLDs are commonly used for personal dosimetry in photon and electron fields. The basic mechanism of thermoluminescence is that energy from ionizing radiation is absorbed in a thermoluminescent (TL) material, and a portion of that energy causes electrons to become trapped at defects in the crystalline structure. When the TL material is subsequently heated, the electrons escape from the traps and return to a lower energy state, accompanied by the release of photons of visible light. The amount of light emitted by a TL material is proportional to the dose absorbed by the material since the last reading.

In principle, incident fast and slow neutrons can be detected in a same detector. Most TLD materials have some sensitivity to fast neutrons, but the dose-equivalent response is significantly lower, and often more energy dependent, than the dose-equivalent response to photons. The reduced dose-equivalent response to neutrons is due to: (1) lower TLD-to-tissue kerma ratios for neutrons than for photons; (2) reduced TL efficiency for high-LET particles produced by neutrons; and (3) the effect of the quality factor being larger than unity, thus decreasing the dose to be measured for a dose equivalent equal to that produced by photons. The sensitivity of TLDs to fast neutrons can be increased by using hydrogenous materials such as a proton radiator in contact with the TL material. Unfortunately, it is difficult to make a detector with a sufficiently intimate contact between the hydrogenous radiator and the TL material that can also withstand the temperature needed to read the TLD.

TLDs are more widely used in albedo dosimeters. TLD materials containing ^{6}Li or ^{10}B are used to detect low-energy (slow) albedo neutrons backscattered from the wearer's body or a phantom. These materials are much more sensitive to slow neutrons than to fast neutrons or photons, due to the large-cross-section reactions $^{6}Li(n,\alpha)^{3}H$ and $^{10}B(n,\alpha)^{7}Li$. The sensitivity of a TL material to slow neutrons can be further enhanced by making it with materials enriched in these isotopes. The materials most often used for slow-neutron detection are enriched lithium fluoride (^{6}LiF:Mg,Ti and ^{6}LiF:Mg,Cu,P), natural lithium borate ($Li_2B_4O_7$:Mn) and enriched lithium borate ($^{6}Li_2{}^{10}B_4O_7$:Mn). Since TLDs are sensitive to photons, there must be a means to determine the net signal due to neutrons in a mixed field. One way to do this is by pairing each detector that is sensitive to slow neutrons with a detector that is not. For example, a ^{6}LiF:Mg,Ti detector may be paired with a ^{7}LiF:Mg,Ti detector with similar photon sensitivity but almost no sensitivity to slow neutrons. The difference in the readings of the two detectors is the slow-neutron reading. In fields where the neutron-photon dose rate ratio is low, the relative difference in the two readings will be small and subject to a large statistical uncertainty.

When such a dosimeter is exposed to the albedo neutrons, but shielded from incident thermal neutrons, it has an approximately dose-equivalent response to incident neutrons from thermal energy to about 10 keV. At higher energies, the response decreases rapidly, to about 1% at 1 MeV (Alsmiller and Barish, 1974). An example for TLD is shown in Figure 2 (Harvey et al., 1969); all albedo dosimeters with a 1/v detector show a similar response. The energy dependence of the response of an albedo neutron dosimeter may be improved by

including in the dosimeter a second detector of the same kind but unshielded from incident thermal neutrons, and applying an algorithm to the readings obtained from the incident-neutron and albedo-neutron detectors. Even with such corrections, the resulting dose-equivalent response of the dosimeter varies greatly with neutron energy at intermediate and high energies. One approach to the design of dosimeters to cover the full range of neutron energies normally encountered (thermal to 20 MeV), is to measure the neutrons in the range up to about 10 keV with an albedo detector and, in addition, the neutrons of energies above this with a fast-neutron detector (see, for example, the discussion by Harvey (1981)).

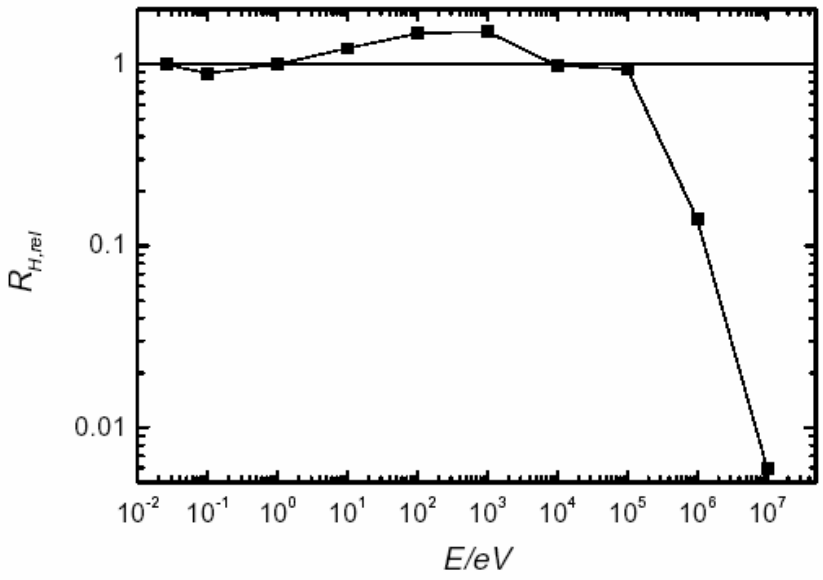

Figure 2. *Typical dose-equivalent response as a function of neutron energy for the Harvey design of TLD albedo dosimeter (adapted from Harvey et al., 1969, for a dosimeter- to-body gap of 2 cm, and using Hp(10) conversion coefficients from ICRU Report 57 (ICRU, 1998)).*

The angle dependence of the dose equivalent response of a TLD albedo neutron dosimeter to unmoderated and moderated ^{252}Cf fission neutrons agrees quite well with that expected for Hp(10), up to an angle of 90° (Tanner et al., 1997; Liu et al., 1990b).

The detection limit for an albedo dosimeter using LiF:Mg,Ti is in the range 20-100 mSv, with the higher values associated with higher-energy neutron fields (Piesch and Burgkhardt, 1988). The response increases linearly with increasing dose, to doses well above normal protection levels. The TL material ^{6}LiF:Mg,Cu,P, which is 10-30 times more sensitive to photons than ^{6}LiF:Mg,Ti, is only about four times more sensitive to thermal neutrons (Nikodemova et al., 1992). This results in a decrease in the relative difference in photon and neutron signals, which increases uncertainty in determining the neutron component of a mixed field. Nonetheless, it provides a lower neutron dose detection threshold. The sensitivity of natural LiF:Mg,Cu,P to unmoderated ^{252}Cf neutrons is less than that of ^{7}LiF:Mg,Ti by about a factor of 5, making it a very effective material for measuring photon dose in the presence of fast neutrons (Horowitz and Shachar, 1988). The response of a TLD is independent of dose rate. TLDs are practically insensitive to environmental influence quantities, such as temperature, pressure and electromagnetic fields. They must be protected from contamination with materials that could interfere with their light emission during reading, and some TLDs are sensitive to visible or ultraviolet light.

Due to the strong energy dependence of the albedo dosimeter response, a single calibration factor cannot be used in different neutron fields with widely varying spectra if accurate dose results are to be obtained. Instead, location-specific calibration factors must be developed, based on a characterization of the neutron energy spectrum at each location. A dosimeter can be used only in a single location during its period of issue, or in several locations with similar neutron spectra. It is necessary to keep a record of the location(s) in

which the dosimeter was used, and to apply the appropriate calibration factor to the reading.

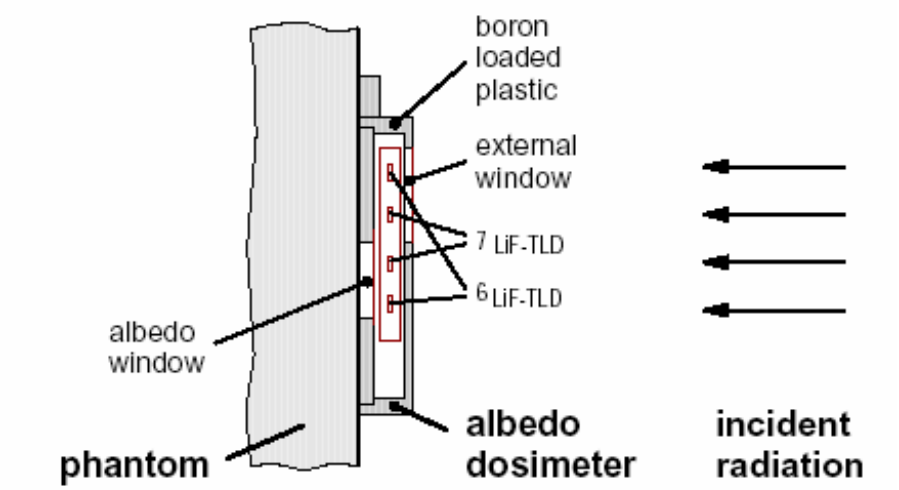

Figure 3. *Schematic drawing of an albedo neutron dosimeter consisting of a boron plastic encapsulation and a card containing two chips each of ^{6}LiF and ^{7}LiF (after Piesch and Burgkhardt, 1985).*

An example of a TLD albedo dosimeter is illustrated in Figure 3. In this schematic design, there are two pairs of ^{6}Li-^{7}Li detectors, one pair on the outside of a thermal neutron absorber, the other pair on the inside (relative to the body). The difference between the readings of the first pair provides a measure of the incident slow- neutron fluence, and the difference between the readings of the second pair provides a measure of the albedo slow-neutron fluence. The ratio of both neutron readings is used to derive a correction factor averaged over the wearing period, taking account of the neutron spectrum in the workplace. A universal albedo neutron dosimeter design of this type was developed in Germany and is widely used (Piesch and Burgkhardt, 1988). A simpler, two-detector dosimeter developed by Harvey et al. (1973) has been in use at nuclear power stations in the UK for 30 years. In a review article, Piesch and Burgkhardt (1985) described these two designs and several others.

To achieve consistent results with currently used albedo dosimeters, it is important that they be held close to the body and that the absorber be either sufficiently large in area or of a suitable shape to ensure that few of the incident thermal neutrons are able to reach the albedo neutron detector. An undesirable consequence of the presence of an absorber is that secondary gamma rays are produced by neutron capture, increasing the photon component of the signal in both detectors, if they are sensitive to photons. While TLDs are used principally for personal neutron dosimetry, they can also be used for neutron area monitoring. Pairs of thermal-neutron-sensitive and -insensitive TLDs are placed inside a moderator (e.g., Esposito et al., 1992). There is a large variation in ambient dose equivalent response with neutron energy, making a careful calibration or correction essential for accurate measurement. In a series of studies in Sweden, TLDs were used inside moderators to evaluate the directional characteristics of neutron fields in nuclear facilities (Lindborg et al., 1995; Drake and Bartlett, 1997; Drake and Kierkegaard, 1999).

In recent years, renewed attention has been devoted to investigating the response of TLDs to high- and low-LET radiations (Geiss et al., 1998; Osvay et al. 1999; Brandan et al., 2002), seeking alternatives to the albedo modality for the measurement of the neutron and photon dose components in mixed radiation fields. One of these approaches relies on the thermoluminescence glow curve analysis, which consists in resolving the individual peaks of the TL signal, utilizing numerical fitting procedures along with analytical representations of the glow peaks based on kinetics models. The glow curve analysis can potentially improve significantly the overall dosimetric performance of TLDs by allowing the discrimination of unstable peaks, without resorting to thermal treatments, as well as of instrumental background and of spurious signal (Gomez-Ros et al. 1999). Moreover, the

thermoluminescence peaks can be analysed in terms of trapping parameters (Bos, 2001), such as the activation energies, based on the track interaction theory (Horowitz et al., 2001). This theory suggests that high-LET particles, such as the products of neutron interactions, populate the traps corresponding to higher-temperature peaks more than low-LET electrons from photon interactions. On these grounds, the analysis of the relative magnitude of the different peaks has been utilised to estimate the dose from the two types of radiation (Schöner et al., 1999), particularly in aviation and space dosimetry investigations.

Another approach recently proposed to derive dose and radiation quality in mixed-radiation and high-energy fields relies on the use of different types of LiF detectors, which have the same atomic composition except for the presence of dopants causing different LET responses (Olko et al., 2002). In this approach, the response of the detectors to particles of different charge and energy is modelled using microdosimetric methods (Olko, 2002). These correlate the probability of TL emission to the specific energy deposited in nanometer size volumes, whose distributions can be derived from analytical models based on Monte Carlo track structure calculations.

While other forms of luminescent detectors, such as radiophotoluminescent glass, have found limited application in neutron dosimetry, great expectations are raised by the more recent technique of optically stimulated luminescence (OSL). Based on laser stimulation, OSL has already had a major impact on the field of photon dosimetry since it presents several advantages over TL methods. As it requires no heating of the phosphors, OSL avoids the need to ensure reproducible temperature ramps as well the problem of thermal quenching of the luminescence. Of particular relevance to neutron dosimetry is that the low-temperature nature of the process permits use of materials which would degrade at high temperatures, among these are some highly-hydrogenated ammonium salts which hold promise due to their neutron sensitivity and tissue-like composition (Le Masson et al., 2004).

4. Etched Track Detectors

The passage of a charged particle through an inorganic or organic insulating material can damage the structure. The damage is generally permanent but may be partly restored or may be modified over time, influenced by factors such as temperature, humidity and the local presence of oxygen or other gases. The particle tracks - the damage ‘trails’, may be viewed directly with an electron microscope in some instances (Silk and Barnes, 1959; Price and Walker, 1962) or may be rendered visible under an optical microscope by etching with a suitable solvent (Young, 1958). The resulting conical etched pits have entrance diameters in the range of a few tenths to a few tens of micrometres. There is a threshold rate of energy deposition and concomitant material damage along a track for it to be made visible by etching. This threshold rate, which depends on the material and the method of the etching, determines the types of charged particle that can be detected (and neutrons via secondary charged particles from conversion processes), their energies and angles of incidence. The measurement, or series of measurements of the developed or developing conical etched pit can be used to determine characteristics of the particle which produced the pit and then allow the identification of the particle type and energy. An introduction to the more general study of track etching and its many applications may be found, for example, in Fleischer et al. (1975) and Durrani and Bull (1975).

For dosimetry applications, the counting of low track densities could be accomplished for etched tracks in thin films by rapid read-out techniques using highly coloured detector films or electronically by the development of spark counting (Cross and Tommasino, 1968; 1970; Lark, 1969). The process of electrochemical etching (Tommasino, 1970; Sohrabi, 1974; Tommasino and Armellini, 1973) greatly increases the size of the etched pits such that they are visible to the unaided eye and can be counted automatically by simple low-power optical systems. Neutron detection using etched-track detectors was initially only possible by means of (n,a) or (n,f) reactions and, for neutron energies above about 1.5 MeV, by means of the detection of recoil nuclei (Józefowicz, 1971). Then, a commonly used plastic, PADC

(polyallyl-diglycol carbonate), often referred to by its trade name CR-39™, was introduced (Cartwright et al., 1978; Cassou and Benton, 1978). PADC is uniquely sensitive to protons. Other track etch materials, notably some forms of cellulose nitrate are also capable of registering protons, but with low sensitivity.

Depending on the etch process used, protons of energies up to about 10 MeV may be detected by PADC, corresponding to LETs down to about 3 keV μm^{-1}. The application of PADC to neutron personal dosimetry was recognised and demonstrated by several authors (Benton et al., 1980; Ruddy et al., 1981; Somogyi and Hunyadi, 1980; Al-Najjar et al., 1979; Griffith et al., 1981). The addition of a converter layer for the neutron energy region from thermal to a few keV (Bartlett et al., 1986) produces a dosimeter with acceptable energy dependence of response for most practical purposes. Since 1980, there has been much effort at many laboratories to develop routine neutron personal dosimetry systems based on the chemical or electrochemical etching of PADC. In spite of problems of plastic consistency there are now several routine services in operation using PADC.

Detailed descriptions of fundamental aspects of etched track dosimetry and of the different etch processes and dosimetric characteristics may be found in two review papers (Tommasino and Harrison, 1985; Harrison and Tommasino, 1985), in the proceedings of a Workshop (Bartlett et al., 1987) and in a recent survey of the status of development in Europe (Harvey et al., 1998) and an investigation of dosimeter performance characteristics (Schraube et al., 1997a). Brief summaries of important aspects are given in the following sections.

The damage trail in a material, which constitutes a charged particle track, is a result of local deposition of energy during the passage of the particle and as such may be related to restricted LET or to lineal event density (Paretzke, 1987) or to radial dose (Butts and Katz, 1967) (see also discussion of Paretzke, 1982). The track is developed to form a pit, of approximately conical shape, by the preferential dissolution of plastic along the particle track by a strong chemical etchant: that is the track etching rate is greater than the bulk etching rate. For an observable track to be formed the ratio of track etch rate to bulk etch rate must exceed some threshold value and this in turn is related to the restricted LET or similar parameter of the particle. The value of this ratio will also determine the maximum ‘acceptance’ angle of incidence for tracks to be made visible. For different particle parameters, the different track etch rates will result in different evolutions of the etched pit shape with time of etching for a given set of etchant parameters (chemical composition, molarity and temperature). The measurement of the dimensions of etched pits and their dependence on etching time allow an estimation of the charged particle’s restricted LET and residual range, and, in some cases, allows identification of particle charge and energy (see Fleischer et al. (1975) or Durrani and Bull (1985) for further details).

In electrochemical etching, an alternating electric field is applied across the detector foil during chemical etching. The field strengths are typically in the range of 20 to 50 kV cm-1 (root mean square) at frequencies in the range 50 Hz to 10 kHz. For pits which attain a sharply pointed shape as the chemical etching proceeds, the field strength is enhanced at the tip and local breakdown of the material leads to catastrophic damage. The characteristic ‘tree’ shaped formation produced has a diameter in the range of ten to several hundred micrometres compared to chemically etched pit diameters of a few tenths to a few tens of micrometres. The electrochemically etched pits are visible to the naked eye and can be counted by simple automated low magnification optical systems. A variation on this process is electro-etching, or blow up, in which small pits which have been produced by chemical etching, or relatively underdeveloped pits produced by low frequency electric field electrochemical etching, or a combination of both, are subjected to a short accelerated high-frequency electro-etch. Electrochemical etching is sometimes preceded by a short chemical etch.

Chemical etching for neutron detection using PADC is frequently preceded by a cleaning etch. This uses a mixture of methanol and sodium hydroxide to remove about 50 mm of the plastic surface without developing tracks. This removes any surface tracks, for example from environmental radon, and any surface imperfections.

The materials most commonly used for neutron detection are polycarbonates, cellulose nitrate, and PADC from various manufacturers. Polycarbonates have been used in many forms but Makrofol™ has proved the most popular. It is inexpensive and can be produced in thin sheets of consistent quality. It can be used as a fission-fragment detector in a fission-foil neutron dosimeter. One example comprises a ^{235}U thermal-neutron sensitive foil and a high-energy threshold detector, ^{232}Th (1.3 MeV) or ^{238}U (1.5 MeV) (Wernli, 1984; Prêtre et al., 1996). Another is a full-range dosimeter using ^{237}Np which has a significant response to intermediate energy neutrons (Harrison, 1978; Harrison et al., 1982; Cross and Ing, 1975). Fission foil dosimeters can be expensive and contain radioactive material. These considerations apply particularly to the ^{237}Np dosimeter.

Polycarbonate can also be used with an appropriate converter as a detector in some of the many designs of albedo dosimeters, having the advantage of no photon sensitivity. As well as responding to alpha particles and fission fragments, polycarbonates are sensitive to recoil nuclei from neutron scattering (Jósefowicz, 1971). The energy threshold of sensitivity to neutrons by this detection mechanism is about 1 MeV. Thin sheets of polycarbonate are suitable for the use of spark counters after etching, a technique frequently used with fission-foil neutron dosimeters. Alternatively, an optimized two-step electrochemical etch process has been developed by Piesch and colleagues (Piesch et al., 1991; Józefowicz et al., 1997) which allows an energy detection threshold of less than 1 MeV with a flat personal-dose equivalent response at normal incidence(within ± 30%) from an energy of 1.5 MeV up to around 50 MeV.

Cellulose nitrate, chemically etched, can be used as an a-particle detector and therefore with an (n,a) converter as a thermal and epithermal neutron detector as in an albedo dosimeter. This approach has been investigated by Médioni et al. (1983) but has not proved entirely successful. By using electrochemical etching, protons can be detected in cellulose nitrate, both from an external radiator and for incident thermal and epithermal neutrons, from the (n,p) reaction on nitrogen (Spurny et al, 1987; Bordy and Médioni, 1991). However problems of high background in one case and the complicated processing and read-out procedures in another case coupled with significant effects due to environmental conditions have hindered progress.

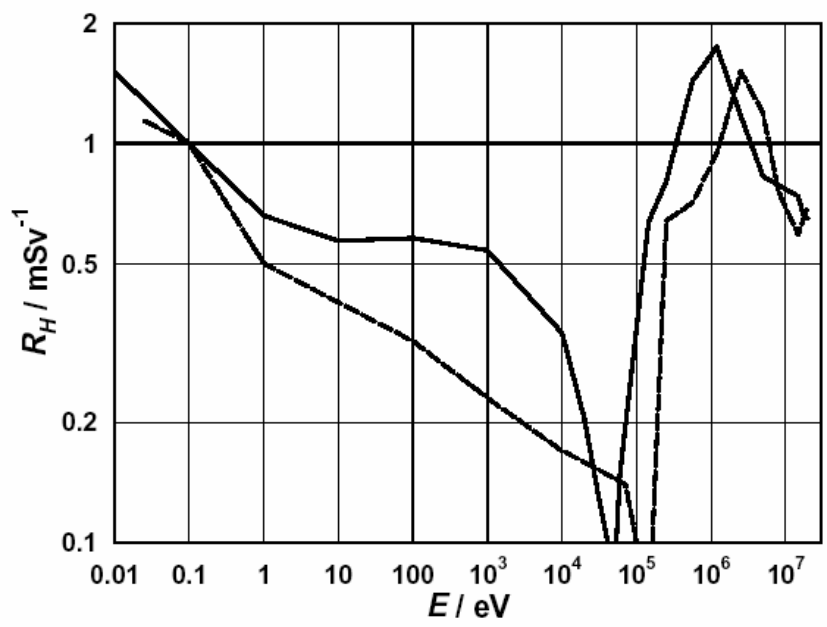

Figure 4 *Energy dependence of the personal dose equivalent response for two operational etched-track dosimetry systems, one chemical etch (dashed line, after Fiechtner and Wernli, 1999), the other electrochemical etch (solid line, after Tanner et al., 2000).*

PADC can detect charged particles over a very wide range of energies, upwards from a lower limit, in terms of LET, of about 3 keV μm^{-1}, subject to particle range and the method of etching and read-out. The use of a converter foil providing the 1/v-type (n,α) and (n,p) reactions and a suitable dosimeter design permits neutron detection in the energy region from thermal to a few keV. Dependent upon the plastic quality and the etching and read-out procedure, recoil protons, and therefore incident fast neutrons, from energies below 100 keV upwards, may be detected. Above 1 MeV or so, recoil nuclei contribute to the response, becoming the dominant contributor at high energies, since recoil protons of energies greater than about 100 MeV, corresponding to LET values less than about 5 keV μm^{-1} are not detected. The energy dependence can be improved by a more complex composition of the converters covering different sections of the PADC detector (Luszik-Bhadra et al., 1994).

Figure 4 shows representative responses as a function of energy for single element (both chemical and electrochemical etch) and multi-element (chemical etch) dosimeters. With chemical etching, and examination of the etched pits under an optical microscope, high sensitivity can be achieved and, if required, measurement of pit parameters can provide the distribution in energy and direction of secondary protons and heavier nuclei incident on the detector surface or generated in the layer removed by etching, and by deconvolution techniques, neutron-spectrometric information. Chemical etching may also be combined with simple rapid read-out procedures (Harvey and Weeks, 1986; Dixon and Williams, 1976) but with some loss of sensitivity and loss of the spectrometric capability. The application of electrochemical etching loses, in general, any spectrometric capability, but allows the use of simple, inexpensive and reliable read-out systems.

In general, the angle dependence of response of a simple planar detector is relatively poor. This can be improved by more complicated multi-element dosimeters (see, for example, Schraube (1983); Harvey (1992)).

The major problem in the routine application of PADC to neutron personal dosimeters has been the batch-to-batch and even sheet-to-sheet variability in both sensitivity and background, particularly the latter, and in some instances other properties such as fading or aging. There is a close link, however, between the sensitivity and background variability and fading and aging characteristics, and the method of manufacture (obviously) and also the method of processing. To ensure acceptable operational performance characteristics of reproducibility and low environmental effects, it has been necessary to compromise with regard to some dosimetric characteristics and also to apply stringent quality acceptance testing of material. There have been recent improvements in the methods of material manufacture (Ahmad and Stejny, 1991).

Although research and development on neutron personal dosimetry using etched track detectors has been in progress at many laboratories for approaching two decades, the application of the technique in routine monitoring is not wide-spread. The main reason for this state of affairs has been the generally poor quality of the PADC, in particular the magnitude and variability of the background track density. An exception was an operational service which moderated the etch conditions and had stringent acceptance criteria on the plastic quality. Nevertheless, it is only recently that the technique has become firmly established as a routine method, with improvements in both plastic quality, and commercial processing and read-out equipment.

When combined with a thermal to a few keV detection element, PADC etched track detectors are suitable for most neutron workplace fields. Both polycarbonate and PADC detectors are suitable for high-energy fields. In fields where there are significant personal dose equivalent contributions in the energy region between a few keV and 100 keV, a correction or suitable normalization must be applied. For dosimeter designs with single planar detectors, or several coplanar or parallel detectors, the dosemeter will have a poor response for neutrons of energy between 100 keV and a few MeV incident at oblique angles. In many workplaces, the relative positions of sources and workers, together with worker movements, will reduce the effect of any deficiency in the angle dependence of response, and both the energy and angle dependence of response in the workplace fields can be incorporated in a normalization factor. Where this is not a practical option, multi-element

designs with better angle response characteristics may need to be used.

More than other passive neutron dosimetry systems, etched-track detectors have benefited from the recent striking advances and general availability of computing and imaging technologies. Over the past decade, processing speed and data storage of personal computers have increased by several orders of magnitude, while high-resolution digital cameras with high gray-scale depth have become common. In combination with motorized-stage microscopes and image-analysis software, this equipment permits investigations of track parameters with extraordinary ease and power. Current R&D focuses on reliability and consistency of track counting by means of image analysers (Pálfalvi et al., 1999), which is an essential element for the automated processing of large amounts of dosemeters by commercial services.

The technique of coincidence counting, long used in high-energy particle-physics, was also brought to unprecedented heights by the new digital-image acquisition and analysis systems. The method consists in the measurement of coincident tracks created by a same particle or a same nuclear reaction across a stack of detector foils held in close contact (Tommasino, 1999; Lengar et al., 2002). In neutron dosimetry with etched-track detectors, coincidence counting can be used to virtually eliminate the plague of background defects. In this case, a pair of detector plates are kept in contact and, when neutron recoil nuclei are produced close enough to their interface, etchable tracks are created on both detectors. Computerised image analysis permits the rapid identification of the tracks present at the same position on both surfaces. These are almost always produced by the same neutron recoils, since track-like background defects are unlikely to occur at a same spot on both detectors. The method may cause the exclusion of real tracks that are only etchable on one of the contact surfaces, but the gain in terms of background rejection is outstanding.

In the past decade, new imaging techniques have also been increasingly applied in etched-track detector research. Among these, coherent light scattering has been introduced and used to extend the linear range of track densities which can be scanned (Groetz et al., 1999; Moore et al.,2002). Confocal microscopy has been used for the three-dimensional reconstruction of the tracks and the analysis of charge and energy of the initiating particle (Vaginay et al., 2001; Meesen at al., 2001). Finally, atomic force microscopy, recording depth and size of the tracks at nanometer levels, has been used to investigate the early stages of track development, to analyse surface roughness and possibly discriminate between tracks and spurious defects in the detectors (Yasuda et al., 1999; Vázquez-López et al., 1999).

Also thanks to this array of new resources, the physics of track formation has been unravelled further in recent years. In particular, a theoretical model for the critical angle has been developed predicting that this angle is not a simple smooth function of the initial particle energy, but splits into two branches (Dörschel et al., 1999). This means that for higher-energy particles the detection efficiency first fades to zero and then rises again for higher angles of incidence, an unexpected behaviour which was verified experimentally (Dörschel et al., 2002). The dependence of the track distributions on the LET of the incident particles has also been thoroughly investigated for measurements of dose and radiation quality in cosmic radiation fields (Spurny et al., 2001; Benton and Benton, 2001; O'Sullivan et al., 2001). Separate studies aiming at aviation and space dosimetry have investigated the response characteristics of etched-track detectors in some recently established high-energy neutron calibrations fields. (Tommasino et al., 2003; Bartlett et al., 2003) All results strongly support the use of these passive detectors for cosmic radiation dosimetry.

5. Superheated Emulsions

Superheated-emulsion neutron detectors are based on a principle first proposed by Apfel (1979). Small droplets of a superheated liquid (i.e., a liquid at a temperature above its normal boiling point) are suspended in a viscoelastic medium. The droplets remain in the liquid phase due to the absence of nucleation sites within the droplets, or at their interface with the host medium. When a neutron interacts with a nucleus inside or near one of the

droplets, the resulting secondary charged particles transfer energy to the droplet, and may cause localized evaporation. A small vapor bubble is formed and begins to expand by vaporizing adjoining liquid. If sufficient energy has been transferred, the bubble will exceed a critical radius and all of the liquid in the droplet will be vaporized. In this case, the bubble becomes visible and persists. If the energy transferred is not sufficient for the bubble to exceed the critical radius, the vapor will recondense. Detailed theories of operation can be found in publications by d'Errico et al. (1997a) and d'Errico (1999).

The sensitivity of these detectors to neutrons of a given energy depends on the atomic composition of the superheated droplets, the number and size of the droplets, and the temperature and pressure of the host medium. The droplets consist of halocarbons, such as Freon™12 (CCl_2F_2), Freon™142B ($C_2H_3ClF_2$), Freon™114 ($C_2Cl_2F_4$) and C-318 (C_4F_8), and hydrocarbons, such as isobutane (C_4H_{10}). Each liquid has a different neutron energy detection threshold at a given temperature and pressure. If the degree of superheat is sufficiently high, detectors containing chlorine are sensitive to thermal and epithermal neutrons via the exoergic $^{35}Cl(n,p)^{35}S$ reaction. The sensitivity of a detector is set during manufacture by controlling the size, number and composition of the droplets it contains. Dosimeters have been made with sensitivities as high as 10 bubbles per microsievert.

Increasing temperature and decreasing pressure both result in a reduction of the threshold neutron energy for bubble formation and an increase in sensitivity above the threshold. The pressure sensitivity provides a convenient on-off switch for the detector: when sufficient pressure is applied to the viscoelastic host medium, the detector becomes completely insensitive to neutrons. The device is turned on simply by releasing the pressure. Normal variations in atmospheric pressure do not result in significant differences in sensitivity. However, the temperature dependence is more severe (Apfel, 1979; Apfel and Roy, 1984). Measurements on an early commercial detector showed an increase in sensitivity of approximately 5%/°C over the range 10°C to 40°C (Cross, 1992). In general, the sensitivity variation with temperature will be a function of the neutron energy and of the chemical composition of the droplets (d'Errico and Alberts, 1994; d'Errico et al., 1995; d'Errico, 1999). At a sufficiently high temperature, the droplets will spontaneously vaporize, setting an upper limit on the operating temperature of the detector.

Several different applications of the basic principle have been developed into commercial neutron detectors. All of them employ a vial or tube, made from glass or plastic, containing a host medium with superheated droplets suspended in it. They differ primarily in the way in which the bubbles are detected and in the way that temperature compensation is achieved. In the devices referred to as bubble damage detectors or simply bubble detectors (BDs), the medium is a polymer gel that is sufficiently rigid so that the bubbles remain in the location where they were formed (Ing and Birnboim, 1984). The number of bubbles formed is proportional to the neutron fluence at a given neutron energy. Counting can be done by eye, for small numbers of bubbles, or by automated techniques. Current versions of this detector are temperature compensated by introducing a low boiling point liquid or an expandable material on top of the gel. The vapor pressure of the liquid or the volume of the material increases with temperature, and compensates for the increase in sensitivity of the droplets with temperature. With compensation, the temperature variation is reduced to within about ±20% over 15-40ºC, relative to the response at 20ºC (Cross, 1992; Chemtob et al., 1995). BDs may be reset through repressurization: after a detector has been used and the bubbles have been counted, a piston cap on top of the detector vial is screwed down manually. The increase in pressure causes the bubbles to recondense, and after a few hours the detector is ready for re-use when the pressure is released again. This process may be repeated through approximately 10 to 20 cycles, after which the bubbles may no longer recondense. In the devices referred to as superheated-drop detectors (SDDs), a less viscous, aqueous gel is used, which allows the bubbles to rise to the surface after they have formed. In the active version of the SDD, an acoustical detector is in contact with the vial containing the medium, so that each time a bubble is formed the pop that the bubble makes can be detected and recorded electronically (Apfel and Roy, 1984). The cumulative dose and dose rate are calculated and displayed in real time, and alarm levels can be set. In this application, the

operating temperature is measured and a temperature correction factor is applied to the number of bubbles detected as part of the dose calculation. A major operational challenge to the use of this type of instrument in the industrial environment has been to discriminate against ambient noise and vibration, which can interfere with the acoustical detection of bubble formation (d'Errico et al., 1997b).

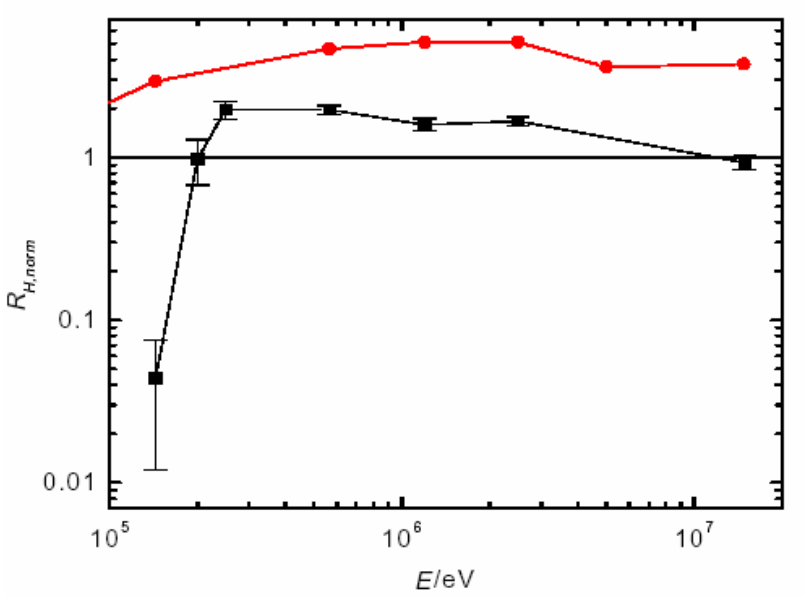

Figure 5. *Average personal dose equivalent response of 5 bubble detectors (at 20 °C, lower curve) and ambient dose equivalent response for a superheated-drop detector (at 30 °C, upper curve), as a function of neutron energy. The error bars show one standard uncertainty. (After Chemtob, 1995; d'Errico and Alberts, 1994).*

The response of superheated emulsions as a function of neutron energy depends strongly on temperature (e.g., d'Errico and Alberts, 1994; Buckner et al., 1994). This dependence on temperature may have contributed to the variability in energy dependence observed in earlier studies, in which the temperature was either not controlled or not reported (Ipe et al., 1988; Perks et al., 1988; Apfel and Lo, 1989; Ipe et al., 1990; Liu and Sims, 1990a; Schwartz and Hunt, 1990; Chemtob et al., 1995; Spurny and Votocková, 1996). Most of these studies found that the dose equivalent response of superheated-emulsion detectors is fairly constant above about 100 keV, but that it is substantially reduced at lower energies. This observed response is in general agreement with theoretical models (Lo and Apfel, 1988; Harper, 1993; d'Errico, 1999). Detectors that are sensitive to thermal neutrons show an enhanced response to intermediate-energy neutrons when the neutrons are thermalized either in the body of the user (or in the test phantom) or in the detector itself (d'Errico and Apfel, 1990; Wang, 1991; d'Errico et al., 1996). The effect of temperature on the energy dependence of a superheated-emulsion detector's response has recently been exploited to provide spectrometric information (d'Errico et al., 1995). In a related study, d'Errico et al. (1996) showed that keeping the bubble detector at a constant temperature of 31.5°C optimizes the energy dependence of the dose equivalent response. At that temperature, the ambient dose equivalent response to a wide range of neutron spectra was generally within 20% of the response to ^{252}Cf neutrons. Examples of the measured energy dependence of dose equivalent response of superheated-emulsion detectors is shown in Figure 5.

The angle dependence of the response of superheated emulsion detectors is approximately isotropic. In order to achieve the angle dependence required for personal monitoring, the detector can be encased in a suitable holder (d'Errico and Alberts, 1994). This approach results in the desired angle dependence and it provides some additional protection from shock, but it increases the size and weight of the dosimeter.

Since superheated emulsions do not show any significant background signal (other

than that due to background neutron radiation), the minimum detectable dose is the dose corresponding to the formation of one bubble. This varies with the detector sensitivity, and typically ranges from 1-10 mSv.

For the BD, the maximum dose that can be measured without repressurization is determined by the maximum number of bubbles that can be counted, which in turn depends on the counting technique. If the bubbles are counted by eye, the maximum number that can be reliably counted is about 50 to 100, depending on the person doing the counting. If automated techniques are used, up to about 500 bubbles can be counted. Within the range of measurable doses, as defined above, the response of BDs is linear with dose (see, for example, Perks et al., 1988).

Active SDDs have a nearly linear response of several thousand counts, depending on the initial number of superheated drops in the detector; at doses producing more than this number of counts, drop depletion becomes significant and corrections are necessary (d'Errico and Apfel, 1990; Ipe et al., 1990, d'Errico and Alberts, 1994). Passive bubble detectors do not appear to have dose-rate dependence. The acoustical signals measured in the active type of superheated-drop detector have a duration of 10 to 15 ms, so there is a dead time of about 20 ms that limits the maximum count rate (d'Errico and Alberts, 1994). An important advantage of all neutron dosimeters based on superheated emulsions is their almost complete insensitivity to photons and electrons with energies below the threshold for photonuclear reactions, i.e. about 6 MeV (Perks et al., 1988; d'Errico and Apfel, 1990; Liu and Sims, 1990; d'Errico et al., 2000c).

Many influence quantities, i.e. quantities that can influence the measurement without being the subject of the measurement (ISO, 1998), affect the readings of superheated-emulsion detectors. As mentioned above, the detectors suffer from temperature sensitivity, although the current versions include means for reducing this effect. The storage time and temperature before irradiation also affect readings, and BDs are affected by the time between sensitization and irradiation, the time between irradiation and reading, and the number of re- uses. The size of the bubbles in a BD increases with time after irradiation, particularly for the first ~24 hours (Perks et al., 1988). Since a bubble-counting device will generally have a minimum resolution, the number of bubbles may seem to increase with time after irradiation. At the other end of the time scale, after several weeks the bubbles will have grown so large that they may start to coalesce, again leading to an apparent decrease in the number of bubbles. Tests of the reproducibility of BD readings after 7 to 24 re-uses have not given completely consistent results. Millett et al. (1991), Spurny and Votocková (1996), and Liu and Sims (1990) reported variations in response consistent with the counting statistics (as low as 20 bubbles in some cases) for detectors with sensitivities in the range ~0.4 to 1.0 μSv^{-1}.

However, a serious drop in sensitivity of low-sensitivity (~0.06 μSv^{-1}) detectors (Liu and Sims, 1990) and considerable variation in the sensitivity of the BDs, especially for the higher-sensitivity detectors (Schulze et al., 1992), have been observed. Uniformity of response from detector to detector was found to be consistent with what would be expected statistically for batches of 15 to 20 BDs and also for the SDD pen dosimeters using neutrons from various radionuclide sources (Schwartz and Hunt, 1990; Chemtob et al., 1995). On the other hand, Ipe et al. (1990) observed large differences in sensitivity to Pu-Be neutrons among different SDDs. In a later study, d'Errico and Alberts (1994) checked for repeatability of the measurements of several SDD vials, including vials from different batches and of different ages up to 9 months old. The reproducibility of response was within 10%, at several different temperatures.

When a BD is subjected to impact, a large number of small bubbles is formed. Since they are normally clustered, these bubbles can be distinguished from bubbles produced by neutrons but make counting the neutron bubbles more difficult.

Active SDDs are designed to discriminate between pressure waves produced by bubble formation and external acoustic or mechanical vibration. While the technique for doing this has improved significantly, there are still problems under extreme conditions (d'Errico et al., 1997b). The calibration of the BD is warranted to be valid for up to three

months after the detector is first activated. The manufacturer recommends frequent repressurization; without this, bubbles become permanent. The vial in the active SDD is intended to be replaced after a total dose of 10 mSv has been recorded, or after three months of use, whichever comes first.

Superheated emulsions are particularly suited for measurement of neutron dose equivalent with high sensitivity in mixed fields with a large photon component. The immediate indication of neutron exposure provided by superheated-emulsion detectors is a useful feature for neutron dose control in areas of high neutron dose rates. The passive BD has the further advantages for personal dosimetry of small size and weight, and it does not require a power supply. The BD does require regular repressurization to maintain its sensitivity constant and to maintain a low detection limit. As a result of this operational constraint and the performance limitations noted in the previous section, the BD is not widely used for personal neutron dosimetry. A version of the active SDD was designed for use as a personal dosimeter, but it proved to be too susceptible to interference from noise and vibration, as well as being too large and heavy. The passive SDD is of a more convenient size, but is rather delicate for use in some industrial applications. Passive bubble detectors are not convenient for routine or long-term area monitoring due to the need to remove them for reading and repressurization. However, they can be used for mapping neutron fields over short exposure times, and they are especially useful at high neutron dose rates and in the presence of high photon fields. They have been used to map neutron fields produced by medical accelerators (Nath et al., 1993; Bourgois et al., 1997; d'Errico et al., 1998), and to measure the dose to aircraft flight crews (Apfel, 1992;Lewis et al., 1994). Active SDDs have been designed as area monitors (installed or portable), and have the advantages of alarm capability, easy reading, light weight, and the possibility of remote readout. Their relatively low sensitivity results in a slow response at low dose rates, making them inconvenient for use as dose rate survey meters.

Research on superheated emulsions has blossomed in recent years. Some studies have analysed the commercial devices in terms of performance tests (Vanhavere et al., 1999, Vanhavere and d'Errico, 2002) and of application in workplaces of the nuclear industry(Vanhavere et al., 1998). Extensive research has taken place on their fundamental radiation physics. In a study with immediate practical implications, a unified parametrisation of the properties of superheated emulsions based on light halocarbons has been achieved by introducing the non-dimensional quantity reduced superheat, defined as $s_T = (T - T_b)/(T_c - T_{b,})$ where T_b and T_c are the boiling and critical temperatures of a halocarbon (d'Errico, 2001). For all the emulsions that have been investigated, a similar correlation has been found between reduced superheat and properties such as neutron detection thresholds, sensitisation to thermal neutrons (in chlorine-bearing emulsions), sensitisation to photons, and ultimate thermodynamic instability (i.e., spontaneous vaporisation). Therefore, from the knowledge of the normal boiling and critical temperatures of a halocarbon, it is possible to predict immediately the main properties of an emulsion.

Other areas in which significant research has taken place are the characterisation of the response to charged particles (Guo et al., 2003), necessary for a full understanding of the detector physics, and to high energy neutrons (Tume et al., 1998; d'Errico et al., 2000), needed in particular for cosmic radiation measurements. The recent availability of new high energy radiation transport codes and calibration facilities have permitted a detailed analysis of the response of the emulsions to neutron up to several hundred MeV. At neutron energies above ~30 MeV, superheated emulsions present a rapidly declining response. To counter this effect, lead shells have been used to enhance the high energy response via the production of secondary neutrons from (n,2n) and other multiplying reactions (Agosteo et al., 2000; Sawamura et al., 2003). A ~40% gain in sensitivity can be achieved by surrounding the detectors with 1 cm of lead, although the light weight desirable for a personal dosemeter is compromised (d'Errico et al., 2002).

6. Direct Ion Storage Devices

A new detector technology, an ionisation chamber with so-called direct ion storage (DIS) (Kahilainen, 1996), has been introduced in the past decade. The principle of direct ion storage is to allow the floating gate of a MOSFET transistor to be in direct contact with a small volume of air, the ionisation chamber. The charge of the floating gate is initially set to a predetermined value and ionisations taking place in the air volume partially discharge the gate. The stored charge at the gate can be read nondestructively with a digital voltmeter; the ΔV is proportional to the number of ionisations, and thus the dose, in the air volume. A small and low-cost DIS passive device for beta and photon radiations, requiring an external reader, as well as an active personnel dosemeter with built-in electrometer and alarm functions have already been developed to a commercial level (Boschung et al., 2002) Application of the direct ion storage principle to neutron dosimetry is possible using paired chambers for the separate determination of the photon and neutron dose components (Fiechtner et al., 2001). The main difficulties for the assessment of neutron dose equivalent lie in achieving sufficient neutron sensitivity as well as an accurate subtraction of the photon component. Ideally, the two chambers should present identical photon sensitivities combined with very different neutron responses.

Prototypes detecting fast neutrons via recoil protons have been built using tissue-equivalent materials for the chamber wall, either A-150 or polyethylene. Thermal/albedo neutron sensitivity has been achieved by incorporating boron nitride in A-150 and lithium nitrate in polyethylene, respectively. Slow neutrons are thus detected via the secondary charged particles of the (n,α) reaction with either ^{10}B or ^{6}Li. Teflon and graphite, materials with low interaction cross sections for neutrons, have been tried for the chamber walls of detectors with low neutron sensitivity. In the most recent version of the paired-chamber DIS device, the photon dose discrimination has been augmented with tin filters, while the neutron energy response has been improved by adding boronated plastic covers (Fiechtner et al., 2004) Figure 6.

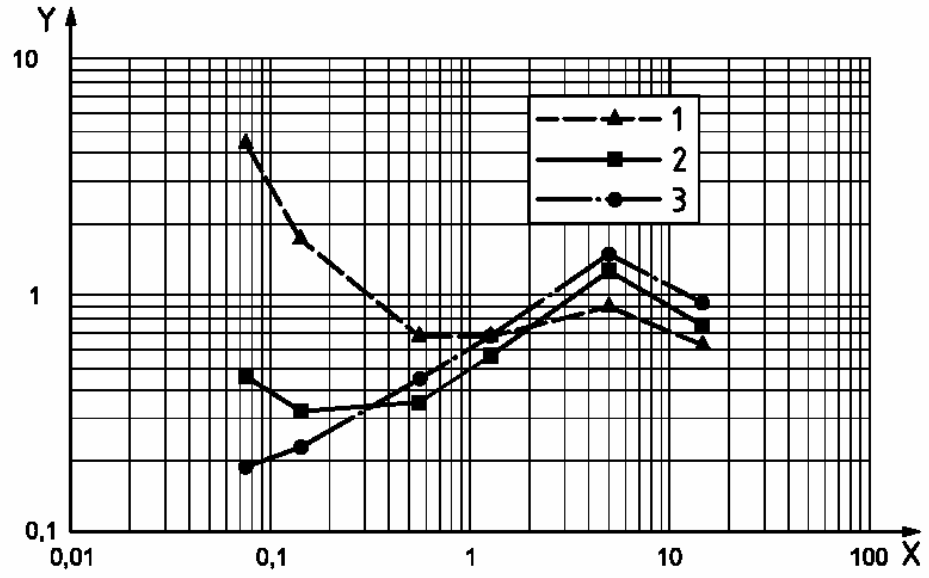

Figure 6. *Personal dose equivalent response of three DIS dosemeter models with different wall materials. (1): 10 % BN-Gr (BN: boronitrite, Gr: graphite); (2): 4 % LiNO3-Gr; (3): 0.1 % BN-Te-Gr (TE: Teflon™) After (Fiechtner et al., 2004)*

At present, the neutron sensitivity of the prototype is lower than required in personal dosimetry and photon discrimination is still somewhat problematic, however, progress

towards a practical device is so encouraging that direct ion storage chambers will be included in an upcoming ISO standard on passive personal neutron dosimetry systems.

7. Conclusions

Neutron dosimetry is a field that evolves slowly, due to the limited demand and the inherent complexity. Thus, passive, solid-state dosimeters are still the most commonly used techniques. Nuclear emulsions and thermoluminescent albedo dosimeters are falling out of favour due to the strong energy dependence of their response. Etched track detectors are increasingly used by commercial dosimetry services applying stringent quality control programs and other techniques for background reduction. Superheated emulsions are slowly finding their way in practical neutron dosimetry, being particularly appreciated for short measurements when high neutron sensitivity is needed together with complete photon discrimination. Finally, new methods based on direct ion storage are emerging, which can be configured either as light-weight, passive, integrating detectors or as electronic dosemeters with instant read-out and alarm functions. These create a bridge between passive and active devices and may well represent the future of personal neutron dosimetry.

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