A SYSTEMATIC APPROACH TO PERSONNEL NEUTRON MONITORING

Richard V. Griffith and Dale E. Hankins

University of California, Lawrence Livermore Laboratory, Livermore, California, 94550 U.S.A.

Introduction

A good personnel dosimetry program requires an integrated approach to personnel dose assessment. No single measurement technique or information source can be relied upon solely to provide accurate dose measurement. This is particularly true for personnel neutron monitoring, because the problem of accurate measurement is so difficult and the personnel dosimeters currently available have severe limitations, preventing a wide range of applications for any one dosimeter type(1). Neutron monitoring requires detection and measurement of neutron doses at 1/10th the level for the accompanying gamma rays. The range of neutron energies generally spans at least nine decades (thermal to 10 MeV), and, in some accelerator facilities at least another decade of energy may be involved. The usual dosimetric problem of angular dependence and body orientation effects add to the difficulty of proper dosimeter interpretation.

It is clear that the information provided by the response of the dosimeter must be used in conjunction with other sources of information to provide the most accurate interpretation of the neutron environment. Other information sources that may provide information necessary for accurate dosimeter interpretation include gamma dosimeter response, instrumental measurements of the gamma and neutron dose rates in the environment, worker stay times, etc. Most dosimeters have a very poor energy response - that is the neutron response does not adequately mimic the dose equivalent conversion curve across the wide range of neutron energies encountered in personnel monitoring. Therefore, a piece of information that is important for accurate neutron dosimetry is the spectral quality of the worker's environment. This information not only improves the accuracy of the dosimeter interpretation, through more accurate assessment of the calibration data, but also serves as a basis for acceptance or rejection of new dosimeters based on their ability to measure the important portion of the dose equivalent spectrum through a radiation facility.

Current Neutron Dosimeters

Before discussing monitoring techniques that can be used in support of a dosimetry program, it is important to review the characteristics of currently available dosimeters. We will place emphasis on the detecting element rather than the system as a whole, because the detector characteristics are the primary limitation of the dosimetry system.

Photographic neutron detectors - NTA film - have been used for operational dosimetry longer than any other dosimeter(2,3). Briefly, the neutron interacts with a proton in the emulsion of a small piece of film, causing the proton to move some distance through that emulsion. When the film is developed, the track of the proton is revealed as a thin trail of silver grains in the film. Dosimetry is done by optical measurement of the number of tracks per unit area using a high magnification optical microscope. In practical use, NTA film has a threshold at about 0.5 to 1 MeV, which is equivalent to a 3 or 4 grain track in the developed emulsion. NTA film is also capable of detecting low energy neutrons from the (n,p) reaction with nitrogen in the emulsion. However, practical experience indicates a poor sensitivity for such low energy neutrons. The energy response of NTA film compared with the ICRP dose equivalent conversion curve for neutrons is shown in Fig. 1a. One of the most serious criticisms of NTA film has been its rapid fading property(4). Although some investigators have had success by packaging the film in hermetically sealed wrapping(5), fading, sensitivity to low energy gammas that fog the film, and the tedious counting involved, are all negative characteristics of NTA.

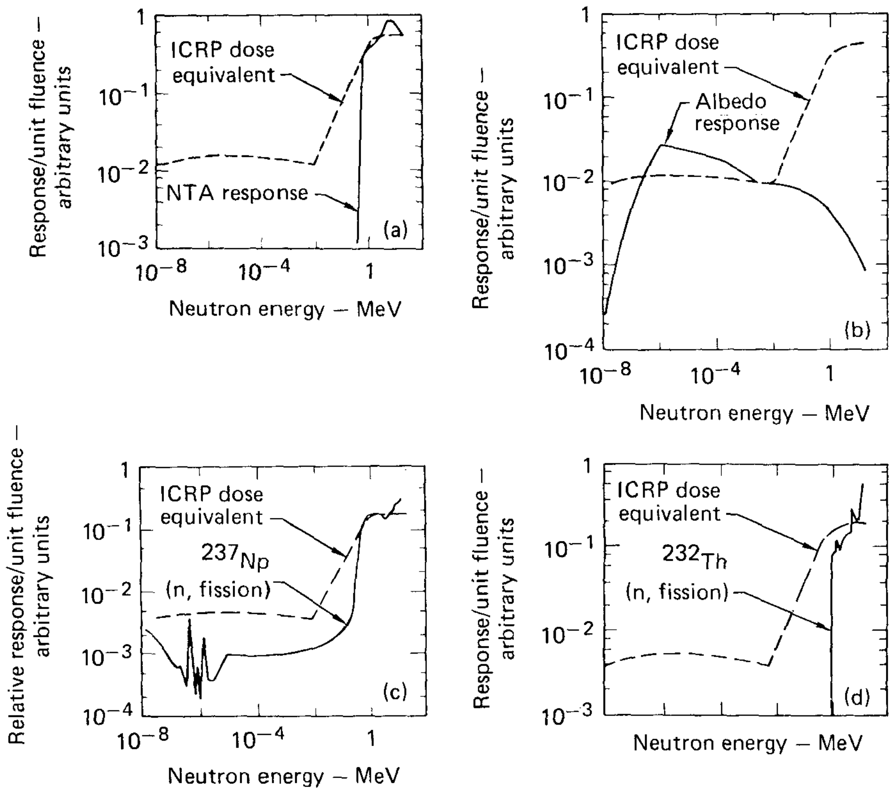

Figure 1. Comparison of the Relative energy responses of personnel neutron dosimeters with the ICRP Dose Equivalent Conversion.

Albedo detectors, which depend on interaction with the human body to thermalize fast neutrons, have had the most rapid increase in use of any of the dosimetry systems used in recent years[6,7,8]. The detecting element is a TLD crystal, having normal or enriched levels of neutron sensitive ^{6}Li. The two distinct advantages of albedo dosimetry are high sensitivity (particularly for low energy neutrons) and the wide availability of automated TLD readout systems. By far, the most significant disadvantage of albedo detectors is a very poor dose equivalent energy response simulation (Fig. 1b). Of all of the dosimeters in use, the albedo system is the most sensitive to spectral variations in the working environment and requires the most supplemental monitoring information. However, for highly moderated neutron environments such as those in nuclear power reactors, albedo dosimeters may be the only real choice.

Two additional dosimeters, which rely on dielectric track etch techniques have been adopted on a much more limited scale than either the NTA or albedo systems. Fission track detectors require the combination of a fissionable radiator and a track registration material. The radiator material (^{237}Np, ^{232}Th, ^{235}U or ^{238}U) is chosen because these nuclides have n,fission cross sections that duplicate all or part of the dose equivalent conversion curve. Fission foil - track etch systems have been used at various laboratories in the United Kingdom, Switzerland, United States, and other countries for about ten years [9,10,11,12]. Of these systems, ^{237}Np dosimeters most faithfully reproduce the dose equivalent conversion curve (Fig. 1c). The biggest drawback of fission foil dosimeters is that the wearer must carry small but significant amounts of radioactive material in the dosimeter. Therefore, they are often issued to personnel only on a limited and controlled basis. Of the nuclides used for this purpose, neptunium has the highest external gamma dose rate from a dosimeter having enough radiator mass to provide sufficient neutron sensitivity. In addition to the disadvantage of having to use radioactive material, the sensitivity of many fission track systems is marginal for routine personnel dosimetry and would probably become unacceptable if higher, more stringent neutron quality factors are adopted. Unlike the NTA type of track detector, the fission track detectors suffer little from the problem of fading[3].

Some laboratories have adopted track detector systems which do not require fissionable irradiators[13,14,15,16]. These detectors rely on direct interaction of the neutrons with light nuclei in the plastic (C, N and O). The charged nuclei recoil, leaving damage tracks that can be revealed by various etching methods. The sensitivity of these systems for fast neutron spectra such as that from a ^{252}Cf fission source is of the order of 50 to 500 mrem, depending on the etching techniques, plastic and the definition of sensitivity used. One of the major problems with direct recoil plastics for routine dosimetry is the relatively high energy thresholds associated with the reactions. It is, however, possible to enhance the low energy response of these detectors using the n,alpha reactions from non-fissionable ^{6}Li or ^{10}B radiators. Unfortunately, little experience, save that of CERN[16], has been obtained with this technique. The manual counting required for dosimeter evaluation is also a limitation. Certainly automated optical systems could be used for this purpose, but they are generally too expensive for small-scale dosimetry programs.

We should point out that the discussion to this point has considered a dosimetry system based on only one detector or one detecting element. In fact, however, it may be necessary, particularly in facilities that have a wide range of neutron spectra, to use a multi-element system. Such systems have been used[16,17,18] and generally involve the combination of an albedo detector with a threshold detector. The responses of the detectors can be combined to synthesize a better simulation of the dose equivalent conversion curve. Moreover, combination systems are, in effect, simple spectrometers. They add to the complexity of the dosimetry, but the improved accuracy and information available may well justify the added effort.

Dosimetry Developments

Perhaps the most promising new detector now being widely investigated is CR-39 plastic. CR-39[19,20,21] is a carbonate, and has physical properties similar to that of glass. The processing of CR-39 for electrochemically etching requires 7 to 10 hours of a combined pre-etch and electrochemical etch. Unlike polycarbonate, the threshold for neutron detection with CR-39 is about 100 keV (Fig. 2), and is capable of detecting less than 20 mrem of fast neutrons. High sensitivity can also be obtained by conventional etching only, however the optical counting of the much smaller tracks is more tedious than when electrochemically etching is used. Although it does not provide as good a replicate of the dose equivalent curve as one would like, it represents a significant potential improvement over other track etch base systems. A personnel dosimetry service with CR-39 is now commercially available.

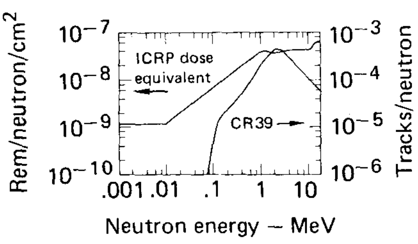

Figure 2. Comparison of the energy response of electrochemically etched CR-39 (after pre-etching (22)) with the ICRP dose equivalent conversion.

A number of other neutron detectors have been and are being investigated for potential personnel dosimetry applications, but each appears to have one or more deficiencies that, for the present, prevent use in operational dosimetry programs. Such detection methods include a super heated drop detector investigated at Yale University[23], lyo-luminescence dosimetry that has been investigated by a number of laboratories[24,25], the development of TLD's having hydrogenous material built into their crystals[26], TSEE (now pursued with much less interest than at one time), and others. One of the more promising TLD based techniques makes use of LET dependent differential glow-peak formation(27). This system continues to be investigated and may be commercially available in some form in the near future.

Neutron Surveys

Neutron dosimeters are interpreted on the basis of calibrations that normalize detector response to dose equivalent. Traditionally, we use unmoderated fast neutron sources - ^{252}Cf, ^{241}AmBe, ^{238}PuBe, etc. - with known neutron emission rates to provide calibrations. We now realize there are usually large differences between the calibration and exposure spectra, making those calibrations inaccurate and uncertain. In recent years, the need for in-field measurements to provide a correction factor to these calibrations has become evident.

The concept of in-field calibrations is that measurements are made with instrumentation having an energy response like the personnel dosimeters. These measurements are then normalized to dose equivalent measurements made at the same locations in the working environment. The normalizations provide the basis for correcting neutron source calibrations. In-field calibrations are necessary only because of spectral differences between the calibration source and working environment. As long as the working area spectra do not change, the measurements need be done only once.

The most traditional and straight forward approach is the survey of a facility with a remmeter (Anderson Braun, spherical moderator, etc.), followed by long-term (hours to days) exposures of personnel dosimeters placed on phantoms at the same locations. This technique is technically sound, but takes a long time and may be severely limited if the dose rates are low. Moreover, the necessary information is not available until the dosimeters are processed, often resulting in the need for resurveying.

A more rapid technique has been developed for facilities using albedo dosimeters(28). A BF_3 detector placed in a 3-inch diameter polyethylene sphere has been shown to have an energy response very similar in shape to that of the albedo dosimeter. The use of phantoms in an initial survey is replaced by a one- or two-minute measurement with the 3-inch moderator. If we use a 9-inch remmeter, a single location can be surveyed in less than 5 minutes, even at millirem dose levels. Additional information on the thermal neutron contribution can be obtained by taking counts with a bare BF_3 probe.

We use the sphere response ratio to identify locations that represent the range of spectral variation in any facility. The survey can then be completed by exposure of a few phantom mounted dosimeters, with the confidence that the proper locations have been selected. We can also sample many more positions in a short time, with a minimum of phantom deployment.

Neutron Spectrometry

The measurement of neutron spectra has, for the most part, been regarded as a laboratory concept, useful in high energy physics, but without practical application in health physics. However, moderated multisphere detector measurements with computer unfolding can now be used to augment conventional survey techniques. The instrumentation required is much less sophisticated than the detectors and electronics used for experimental physics applications, and well within the capability and budget of a health physics program. As an extension of simpler survey methods, multisphere measurements yield spectral and dose equivalent information over the full range of occupational neutron energies. This information can then be used to estimate the error in response of portable remmeters, as well as allowing the health physicist to predict the spectrum weighted response of any personnel monitor in use or considered for use at the facility. The spectra give the health physicist the most clear view of the facility neutron environment.

Health physicists have used Bonner spheres for 20 years[29], but recent computer unfolding codes[30,31] and response calculations[32] contribute to making simple, accurate spectral measurements. New generations of commercially available portable pulse height analyzers make in-field use of multisphere much more mobile. At LLL, we use a portable analyzer, a ^{6}LiF scintillation detector and 3, 5, 8, 10 and 12 inch spheres of polyethylene to make the necessary measurements. The detector is used, in turn, in each of the spheres together with bare and cadmium covered measurements. The detector pulse height responses from the ^{6}Li(n,alpha) reaction in each of the seven detector-moderator configurations are used as input for the unfolding code. The spectra determined have poor resolution qualities, but high resolution is not essential for neutron health protection.

In practice, we make spectrum measurements at key facility locations identified during the detector-remmeter survey described above. We choose these locations to represent the range of spectral variation implied from the range of 3/9 inch ratios. Usually only about three or four locations are measured with this system. Although we use a computer to fully unfold the spectra, the responses of the 3, 8 and 12 inch detector measurements can be used as input for simple matrix inversion programs available on programmable hand calculators, to obtain dose equivalent estimates that are within 15% of the fully unfolded calculations. This gives us an immediate comparison with the remmeter results before leaving the area. Obvious errors in the data can be detected, allowing remeasurement without having to return days later.

We have used the 3/9 inch sphere ratio technique, with multisphere spectrometry to survey our own facilities (a high flux 14 MeV neutron generator, transuranic isotope storage vaults and glove box facilities, a 3 MW pool type reactor and our own neutron calibration facility), as well as a number of power reactors through the United States. The survey technique has significantly improved dosimeter calibrations. The spectral information has been used (even at dose equivalent levels as low as 0.1 mrem per hour) to predict the poor performance of certain threshold detectors in heavily moderated environments, as well as determining the effective over-response of moderated remmeters used in the facilities.

Summary

NTA film and albedo detectors represent the major portion of personnel dosimeters now used for occupational neutron monitoring. However, recent attention to the spectral response of these systems has demonstrated the need for detectors that have a better match to the fields being monitored. Recent developments in direct recoil track etch dosimeters present some intriguing alternatives, and careful use of ^{237}Np fission fragment detectors offers the advantage of a good dose equivalent spectral match. Work continues on a number of other new detector mechanisms, but problems with sensitivity, energy response, gamma interference, etc. continue to prevent development of most mechanisms into viable personnel dosimeters. Current dosimeter limitations make a systematic approach to personnel neutron monitoring particularly important. Techniques have been developed and tested, using available portable survey instruments, that significantly improve the quality of dosimeter interpretation. Even simple spectrometry can be done with modest effort, significantly improving the health physicists ability to provide accurate neutron monitoring.

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