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Personnel Neutron Dose Assessment Upgrade

Volume 1: Personnel Neutron Dosimetry Assessment

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July 1988

Prepared for
the U.S. Department of Energy
Assistant Secretary for
Environment, Safety, and Health
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PERSONNEL NEUTRON DOSE ASSESSMENT UPGRADE

VOLUME 1: PERSONNEL NEUTRON DOSIMETRY ASSESSMENT

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FOREWORD

Neutron dosimetry is an essential part of the U.S. Department of Energy (DOE) personnel dosimetry program. Historically, nuclear track emulsion dosimeters and thermoluminescent-albedo dosimeters (TLDs) have been used for neutron dosimetry at DOE facilities. Both dosimeters have energy dependent responses requiring accurate knowledge of the neutron energy spectra to properly interpret their results. Until recently, technology difficulties precluded the rapid assessment of neutron spectra necessary to accurately interpret dosimetry results. Thus, dosimetry analysts have used a conservative approach in estimating neutron dose by assuming the existence of high energy neutrons wherein maximum quality factors are used in the conversion of neutron absorbed dose to rem. To improve the state of art of neutron dose assessment and to respond to the need for enhanced accuracy dictated by recent changes to the neutron quality factor, the DOE Office of Nuclear Safety has sponsored research over the past eight years to enhance neutron measurement techniques. This effort has been coordinated among DOE contractors with a goal of providing the most effective system. Results of this effort are being reported in a three volume series entitled, Personnel Neutron Dose Assessment Upgrade (PNL-6620). This report is Volume 1: Personnel Neutron Dosimetry Assessment of that series. The other reports are Volume 2: Field Neutron Spectrometer for Health Physics Application, and Volume 3: Computer Code Listing for the Field Neutron Spectrometer.

This report, Volume 1: Personnel Neutron Dosimetry Assessment, provides guidance on the characteristics, use, and calibration of personnel neutron dosimeters with particular emphasis on new dosimetry development. Recent technological advances in neutron dosimeters and instruments have resulted in the development of dosimeters especially suited to specific neutron energies found in various work places. The report is applicable to dosimetry responding to neutron energies ranging from thermal to less than 20 MeV. The background for general neutron dosimetry requirements is provided, as well as relevant federal regulations and other standards. To provide an appreciation of the limitations of current dosimetry, the characteristics of personnel

neutron dosimeters are discussed, with particular attention paid to systems currently used at DOE and DOE-contractor facilities, i.e., nuclear track emulsion and thermoluminescent albedo.

The combination TLD/TED which was recently developed is discussed in terms of field application, theory of operation, processing, readout, and interpretation, as well as advantages and disadvantages in field use. The procedures required for occupational neutron dosimetry are discussed, including radiation monitoring, wearing of dosimeters, exchange periods, dose equivalent evaluations, and documentation of neutron exposures. Finally, discussions on dosimeter testing, maintenance, and calibration are provided including selection of calibration sources, effects of irradiation geometries, lower limits of detectability, fading, frequency of calibration, spectrometry, and quality control.

The application of the new CR-39 dosimetry (TLD/TED) used in conjunction with the recently developed portable neutron spectrometer reported in Volume 2: Field Neutron Spectrometer for Health Physics Applications should provide a considerably improved system for neutron dose assessment. Accurate neutron dose estimates require the use of appropriate quality factor (Q) and the selection of Q is dependent on knowledge of neutron spectra. The system described herein will provide spectra information when used in conjunction with the portable neutron spectrometer. Thus, a more realistic determination of Q can be made to derive accurate estimates of neutron dose.

Revisions in the risk estimates for radiation effects make it increasingly important that attention continue to be focused on accurate dosimetry used to control occupational exposure. In the interest of worker protection, we will continue to seek methods of improving measurements.

Edward J. Vallario
Acting Director
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ABSTRACT

This report provides guidance on the characteristics, use, and calibration criteria for personnel neutron dosimeters. The report is applicable for neutrons with energies ranging from thermal to less than 20 MeV. Background for general neutron dosimetry requirements is provided, as is relevant Federal regulations and other standards. The characteristics of personnel neutron dosimeters are discussed, with particular attention paid to passive neutron dosimetry systems. Two of the systems discussed are used at DOE and DOE-contractor facilities (nuclear track emulsion and thermoluminescent-albedo) and another (the combination TLD/TED) was recently developed. Topics discussed in the field applications of these dosimeters include their theory of operation, their processing, readout, and interpretation, and their advantages and disadvantages for field use. The procedures required for occupational neutron dosimetry are discussed, including radiation monitoring and the wearing of dosimeters, their exchange periods, dose equivalent evaluations, and the documenting of neutron exposures. Finally, the coverage of dosimeter testing, maintenance, and calibration includes guidance on the selection of calibration sources, the effects of irradiation geometries, lower limits of detectability, fading, frequency of calibration, spectrometry, and quality control.

EXECUTIVE SUMMARY

The purpose of personnel dosimetry is to measure an individual's exposure to all applicable radiation types, so that the risk of undesirable effects can be managed. Historically, nuclear track emulsion dosimeters and thermoluminescent-albedo dosimeters (TLDs) have been used for neutron dosimetry at Department of Energy (DOE) facilities. Both dosimeters have energy dependent responses requiring accurate knowledge of the neutron energy spectra to properly interpret their results.

Recent technological advances in neutron dosimeters and instruments have resulted in dosimeters especially suited to specific neutron energies found in various work places and pointed out deficiencies in each of them for some neutron environments. These advances have been in both active and passive dosimeters, as well as in field neutron spectrometers. The primary consideration in selecting passive neutron dosimeters is the energy of the neutrons to which the wearer of the dosimeter will be exposed. Dosimeter performance is affected to a lesser degree by the relative magnitude of the other types of radiation that may be present, the minimum neutron dose equivalent to be detected, the direction of the radiation, and the manner in which the dosimeter is worn.

Three passive dosimeters are discussed in this report: nuclear track emulsion dosimeters, TLDs, and proton recoil track-etch dosimeters (TED). Active dosimeters and other types of passive dosimeters are briefly discussed in Appendix B.

Nuclear track emulsion dosimeters are widely used to monitor the exposure of individuals to fast neutrons at DOE accelerators. Boron- or lithium-loaded emulsions are available for thermal neutron detection. The dosimeter consists of a sensitive silver bromide emulsion bonded to a cellulose triacetate base. The number of recoil proton tracks per unit area of film emulsion is proportional to the exposure to neutrons with energy greater than about 0.5 MeV. The dosimeter approximates dose equivalent between 0.5 and 3.5 MeV, but it begins to overestimate dose equivalent at energies greater than 3.5 MeV.

Disadvantages of nuclear track emulsion dosimeters include their sensitivity to gamma rays. Approximately one rem of gamma produces fogging of the film to the point where it is unreadable for neutrons. Fading of the latent image with time can be significant. The rate of fading increases with relative humidity, temperature, oxygen in the atmosphere in contact with the emulsion, decreasing specific ionization of the incident particles, decreasing emulsion pH, and decreasing grain size. Thus, accuracy may suffer from long exposures. Statistical accuracy and energy dependence are also major disadvantages of nuclear track emulsions. The response (tracks/rem) varies by a factor of 2 over the neutron energy range from 0.7 to 14 MeV.

The most widely used personnel neutron dosimeter at DOE facilities is the TLD, which consists of ^{6}LiF detectors and ^{7}LiF detectors. Lithium is sensitive to slow neutrons and relative insensitive to fast neutrons. The pair of detectors made from ^{6}LiF which are sensitive to neutrons and photons, and the pair of ^{7}LiF detectors are sensitive to photons only. The neutron response is found by subtracting the photon response from the neutron and photon response.

The major advantages of TLDs are that they give some indication when exposed to a significant neutron dose, their readout is simple and can be automated, and they are insensitive to humidity and moderate mechanical shock. They are inexpensive and can be reused. Their greatest disadvantage is their dependence upon the energy of the incident neutrons. The dose equivalent can be in error by a factor of 10 if the dosimeter is not properly calibrated. Moreover, they are not useful at neutron energies above 1 MeV. Therefore, the neutron spectra in the workplace must be known, and the dosimeters must be calibrated for neutrons of the energy that they are to measure.

Proton recoil track-etch dosimeters (TED) are based on neutrons interacting with hydrogen in certain plastics or radiators to produce recoil protons with high elastic scattering cross sections. These protons break the molecular chain, producing damage sites at which preferential etching can be accomplished in a strong basic solution with an electrical potential applied across the TED. A dosimetry grade CR-39, the polymer of allyl diglycol

carbonate, has been developed that is highly sensitive to chain scission by radiation. The CR-39 has a dense, uniform molecular structure and is optically transparent, which facilitates readout.

The CR-39 does not have the energy dependence that exists with albedo neutron dosimeters exposed to fast neutrons, and it does not have the fading and photon sensitivity problems that nuclear track emulsions have. Its other advantages include stability to high humidity and temperatures to 50°C, accuracy to ±25% at 10 mrem, and a lower limit of detection of 10 mrem in the energy range of 100 keV to 18 MeV. The major disadvantage of TEDs is their angular dependence. The response drops to about 20% as the angle of incident neutrons approaches 90°. Other disadvantages include sensitivities to UV light, high temperature, and alpha particles. Their useful energy range is 100 keV to 18 MeV, but there is a loss in sensitivity above about 5 MeV.

Calibration of personnel neutron dosimeters is essential to their accuracy. Calibration should be based on a technique that is traceable to the National Bureau of Standards (NBS) as well as on the response of the dosimeter in the field environment and the manner in which it is used. The influence of the work environment can be incorporated into the dosimeter calibration in two ways: 1) by measuring the neutron flux density in the work place as a function of neutron energy and calculating the dosimeter response or 2) by exposing the dosimeters to a known dose equivalent in the work place and using spectrometric methods to determine dose equivalent. Spectrometric methods should be used to increase the accuracy of existing personnel dosimeters and instruments. Spectral information can be used to calculate quality factors and dose conversion factors to account for future changes. Effective dose equivalent can be calculated if the neutron energy spectra and irradiation geometry data are known. Therefore, spectral data in the work place are essential to personnel neutron dosimetry.

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GLOSSARY

Absorbed Dose (D). The energy imparted to matter in a volume element by ionizing radiation divided by the mass of irradiated material in that volume element. The special unit is the rad. The SI unit is the gray (Gy). One Gy equals 100 rad.

Absorber. A material with a high neutron absorption cross section.

Accident Dosimetry. The determination of high levels of absorbed dose resulting from uncontrolled events.

Accreditation. The process of approval for a program which uses personnel dosimeters to measure, report, and record dose equivalents received by radiation workers. (See DOELAP and NVLAP.)

Accuracy. The degree of agreement of the observed value with the correct value of the quantity being measured.

Active Dosimeter. A system, such as a total dose meter or pocket ion chamber, which gives real time readout of dose information continuously and does not require an external readout system.

ALARA. As low as reasonably achievable.

Angular Dependence. Response of the detector as a function of the angle of incidence of the radiation being detected.

Calibration. The check or correction of the accuracy of a measuring instrument or dosimeter to assure proper operational characteristics.

Combination Dosimeter. A dosimeter that consists of two or more different types of radiation-sensitive elements, such as the combination thermoluminescent/track etch dosimeter (TLD/TED), each with their own unique energy response and range.

Controlled Area. Any area to which access is controlled in order to protect individuals from exposure to radiation and radioactive materials.

CR-39. Trade name for Columbia Resin-39, produced by Pittsburgh Plate Glass, Pittsburgh, Pennsylvania. A specific polycarbonate polymer made of allyl diglycol carbonate that is sensitive to heavy charged particles.

Cross Section. Effective target area for a specified nuclear interaction. The cross section is a measure of the probability for the interaction. It is usually expressed in barns. One barn equals 10^{-24} cm^2.

DOELAP. Department of Energy Laboratory Accreditation Program.

Detection Limit. The extreme of detection or quantification for the radiation of interest by the instrument as a whole or an individual readout scale. The lower detection limit is defined on the next page. The upper detection limit is the maximum quantifiable instrument response or reading.

Dose Equivalent (H). The product of the absorbed dose (D), the quality factor (Q), and any other modifying factors. The special unit is the rem. When D is expressed in Gy, H is in Sieverts (Sv). 1 Sv = 100 rem.

Dosimeter. A combination of absorber(s) and radiation-sensitive element(s) packaged to provide a cumulative record of the wearer's absorbed dose or dose equivalent.

Dosimeter Element. A volume of radiation-sensitive material within a dosimeter. Examples: thermoluminescent chip and track-etch foil.

Dosimetry System. The dosimeters, the related data-collection and processing instruments, and the techniques required to estimate the dose equivalent received by exposed individuals.

Effective Dose Equivalent. Weighted sum of the dose equivalent to the exposed critical organs in the body.

Energy Dependence. A change in instrument or dosimeter response per unit of radiation quantity, as a function of radiation energy.

Exchange Period. The length of time for which a dosimeter is issued to an individual for the purpose of dose determination.

Fast Neutrons. Neutrons of energies above 10 keV.

Fluence. The number of particles which enter a sphere per unit of cross sectional area of that sphere.

Free Field. Without the human body present.

Intermediate Neutrons. Neutrons with energies from 1 eV to 10 keV.

Gray (Gy). The SI special unit of absorbed dose. One Gy equals one J/kg or 100 rad.

Kerma. The initial total kinetic energy of directly ionizing particles ejected by the action of indirectly ionizing radiation per unit mass of specified material.

Lineal Energy (y). The quotient of ε and $\bar{l}$, where ε is the energy imparted to the matter in a volume of interest by an energy deposition event and $\bar{l}$ is the mean chord length in that volume.

Linear Energy Transfer (LET). The average energy lost by a directly ionizing particle per unit distance of its travel in a medium.

Lower Detection Limit. The minimum evaluated dose equivalent for which the readout value of a dosimeter is significantly different (at least 95% confidence level) from the readout value for unexposed dosimeters.

Monitoring. Periodic or continuous determination of the amount of ionizing radiation exposure received by an individual or individuals.

Monte Carlo. A computer method for solving problems of physics, such as those of neutron transport, by determining the history of a large number of elementary events by the application of the mathematical theory of random processes.

Neutron. An uncharged elementary particle with a mass slightly greater than that of the proton. It is found in the nucleus of every atom heavier than hydrogen.

Nuclear Track Emulsion. The oldest type of passive personnel neutron dosimeter still in use at DOE facilities. It records individual charged-particle tracks. Kodak Personal Neutron Monitoring Film Packet, Type A (NTA) is the most widely used film for measuring fast neutrons at DOE accelerators.

NVLAP. National Voluntary Laboratory Accreditation Program.

Passive Dosimeter. A system, such as NTA film, that accumulates a signal proportional to dose equivalent. An external readout system is required to evaluate the dose equivalent after the dosimeter has been exposed to radiation.

Quality Factor (Q). The modifying factor selected to account for the difference in the biological effects of equal absorbed doses of different types of radiation.

Rad. The special unit of absorbed dose. One rad equals 100 ergs per gram.

Radiation Worker. A person who is exposed or is likely to be exposed to radiation in the course of his work. Defined by DOE as any individual who, by qualification through documented training, is allowed to enter controlled radiation zones unescorted.

Rem. The special unit of dose equivalent. The dose equivalent in rem is numerically equal to the absorbed dose in rad multiplied by the quality factor, the distribution factor, and any other necessary modifying factors.

Sievert (Sv). The SI unit of dose equivalent. One hundred rem equal one Sievert.

Spectrum. The energy spectrum. The distribution of the fluence as a function of energy.

Track Etch Dosimeter (TED). A dosimeter based on the use of track etch detectors. Examples: CR-39, polycarbonate, Lexan.

Tissue Equivalent Proportional Counter (TEPC). A device that measures the absorbed neutron dose and determines quality factors from lineal energy and LET distributions.

Thermoluminescent Dosimeter (TLD). An integrating detector that uses a phosphor such as LiF:(mgTl) or $CaSO_4$:Mn that is sensitive to ionizing radiation. The phosphor stores some of the energy of the ionization by trapped electrons and releases the energy as low-energy photons (light) when heated.

Thermal Neutrons. Neutrons in thermal equilibrium with their surroundings. In this document, all neutrons with energies of less than about 1 eV are termed "thermal."

Total Dose Meter. An active pocket-sized dosimeter capable of measuring any penetrating ionizing radiation. It uses a TEPC detector.

Track Etch Detector. A dielectric material that is capable of detecting and recording the interactions of individual heavy charged particles (protons, alpha particles, and charged nuclei). The particles can result either from direct neutron interactions in the material or from an external radiator.

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1.0 INTRODUCTION

Developing a neutron dosimetry program raises difficult problems. Ideally, personnel dosimeters should respond accurately over a large range of neutron energies and should follow a dose equivalent response function that is not physically measurable. It should perform these functions in the presence of varying amounts of photon and beta radiation of various energies. No single dosimeter system has these characteristics. Therefore, systems using more than one dosimeter type have been developed. Even with these systems, it may be necessary to combine the data obtained from the personnel dosimetry system with information from other neutron monitoring techniques to make proper individual assessments of dose equivalent.

This report discusses characteristics, use, and calibration criteria for passive and active neutron dosimeter systems worn by individuals. The report is applicable for neutrons with energies ranging from thermal to values less than 20 MeV. Guidance in this report applies to devices worn by individuals, as opposed to hand-held or fixed-area instrumentation. The report only briefly discusses the dosimetry necessary for criticality accidents and does not address extremity measurements. Criticality (nuclear accident) dosimetry guidance is given in the U.S. Department of Energy (DOE) Order 5480.1 (1981), Chapter XI, Section 4.c. Guidance on extremity dosimetry is still being developed, and the current status of extremity dosimetry performance, use, and calibration at DOE facilities is presented in the Pacific Northwest Laboratory[a] (PNL) report, Extremity Dosimetry at U.S. Department of Energy Facilities, PNL-5831 (Harty et al. 1986).

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2.0 GENERAL NEUTRON DOSIMETRY REQUIREMENTS

Historically at DOE facilities two types of personnel neutron dosimeters have been in routine use: nuclear track emulsion film and thermoluminescent (TLD)-albedo. Both dosimeters have responses that are dependent on nuclear energy. In addition, the dosimeters have limited energy ranges. Therefore, the neutron energy spectra must be known to properly interpret the dosimeter results. To overcome these problems, a field neutron spectrometer and new dosimeter types, some of which contain multiple detecting elements, have been developed. System development has been largely justified by the need for improved neutron dosimetry, as discussed in the following sections.

2.1 BACKGROUND

The purpose of personnel dosimetry is to measure an individual's exposure to all applicable radiation types, so that the risk of undesired effects can be managed. Neutron dosimetry is particularly troublesome for several reasons. The primary reason is that neutrons interact strongly with tissue, and the mechanisms available for neutron detection are not usually directly related to the tissue damage processes. In addition, self-shielding in a hydrogenous object of human dimensions (either person or phantom) can cause the neutron dose at any given point to vary by as much as a factor of 100, depending on the direction of incidence and its energy. Because of the difference in biological effectiveness of equal absorbed doses of neutrons and photons, a quality factor (Q) is applied to absorbed doses to calculate the dose equivlaents. The Q for neutrons varies from 2 to 11 depending on the neutron energy. However, the quality factor is not a simple, physically observable quantity, and evidence appears to substantiate the need for an increase in Q. Selection of new, more appropriate Qs is being actively debated. If the neutron Qs are raised, personnel neutron dose equivalent as a function of the neutron energies must be accurately determined.

2.2 REQUIREMENTS

The requirements for radiation protection at DOE facilities are contained in DOE Order 5480.1, Chapter XI, "Requirements for Radiation Protection" (DOE 1981). Chapter XI establishes radiation protection standards and requirements for OOE and DOE contractor operations based upon the recommendations of the Environmental Protection Agency (EPA) and the National Council on Radiation Protection and Measurement (NCRP). It contains little guidance specific to personnel neutron dosimeters. Therefore, this document supplements OOE Order 5480.1, Chapter XI, specifically to address neutron dosimetry. The need for additional guidance results from the on-going development and implementation in the field of new dosimetry systems, e.g., field neutron spectrometer, combination thermoluminescent/track-etch dosimeters (TLD/TED), total dose meter, and others.

The NCRP has published several reports whose recommendations for personnel dosimetry are generally followed at DOE facilities. Protection Against Neutron Radiation, NCRP Report No. 38 (1971), contains information important for personnel dosimetry, such as definitions, dose equivalent limits, quality factors, conversion factors for changing flux to dose equivalent rate, and depth-dose relationships for neutrons of various energies. Instrumentation and Monitoring Methods for Radiation Protection, NCRP Report No. 57 (1978), contains information and suggestions on types of neutron dosimeters, methods for estimating whole-body or organ doses and dose equivalents, as well as dosimeter exchange periods, accuracy requirements, and records.

The U.S. Nuclear Regulatory Commission (NRC) has also developed performance standards which may be used as guidance but that do not apply specifically to OOE contractors. The standards with which NRC licensees must comply are contained in three documents: "Personnel Monitoring," Section 20.202 of Title 10, Chapter 20, U.S. Code of Federal Regulations (10 CFR 20); "Personnel Neutron Dosimeters," Regulatory Guide 8.14 (NRC 1980); and Personnel Neutron Dosimeters (Neutron Energies Less Than 20 MeV) (ANSI 1976). Some of these requirements are summarized as follows:

1. Personnel neutron dosimeters shall be capable of measuring neutron dose equivalents in the range of 10 mrem to 1000 rem[(a)] per the exchange period of the dosimeters.
2. The accuracy of 10 dosimeters exposed to an unmoderated ^{252}Cf source in the range of 100 mrem to 3 rem shall be within ±50% of the true dose equivalent.
3. The neutron dosimeter shall be able to measure 1 rem of neutrons in the presence of 3 rem of gamma rays with an energy ≥500 keV in mixed radiation fields.
4. The neutron dosimeter shall meet the above requirements when subjected to the following environmental conditions:
   a. temperature extremes of 0°C and 45°C for 1 week
   b. relative humidity of 90% for 1 week
   c. mechanical shock from a drop from a height of 1.5 m (4.9 ft)
   d. exposure to light (sunlight or normal room light) for the extent of the dosimetry period.

In addition, the ANSI Standard N13.11, Personnel Dosimetry Performance-Criteria for Testing (ANSI 1983) lists criteria to be used for testing personnel dosimeters.

Performance characteristics for neutron dosimeters are provided in Appendix A.

(a) Quality factors are not necessarily defined for high-dose conditions. Quality factors were derived for low exposures considering cancer induction as an endpoint.

3.0 NEUTRON DOSIMETRY SYSTEMS

Recent technological advancements in neutron dosimetry devices have resulted in the availability of dosimeters especially suited to specific neutron energies found in various workplaces and pointed out deficiencies in each of them in some neutron environments. Regulatory changes and the recognition of the possibility of greater risk from the exposure to neutrons relative to other radiations now prompts DOE to provide the best possible dosimetry to workers likely to be exposed to neutrons. There are two types of dosimetry systems from which to choose: passive systems and active systems. Passive dosimeters store dose data for intermittent readout using an external system and are discussed in Section 3.2. Active dosimeters provide real-time dose information without the requirement for external readout; they are discussed in Appendix B.

3.1 SELECTION

Several considerations are important in selecting, calibrating, and using a personnel neutron dosimetry system: the spectrum of the neutrons to be monitored, the minimum neutron dose equivalent to be detected, and the relative magnitude of other types of ionizing radiation that may be present. Beyond these considerations, other factors should be evaluated that relate to either the unique characteristics of the dosimeter being considered, or to the specific requirements of the monitoring program.

The dosimeter performance is an important consideration in the selection process. The performance of the dosimetry system should be characterized in relation to the working environment(s) in which it is to be used. Current neutron dosimeter performance is highly dependent on the energy of the neutron radiation, on the manner in which it is used, and on the calibration techniques. Care should be taken to accurately relate the performance of the dosimetry system in a laboratory environment to performance during actual field use.

The dosimeter performance is dependent upon the location of the dosimeter and the way in which it is worn. It is important to know the effects of photon interference and radiation directionality on dosimeter response.

Selection of a personnel neutron dosimeter should be based initially on the neutron spectrum normally encountered in the work area. Currently, different dosimeter types are required to detect thermal, intermediate, or fast neutrons.

3.2 PASSIVE SYSTEMS

This section discusses the three passive neutron dosimetry systems widely used by DOE and DOE contractors at present and the recently developed combination dosimeter. (The five figures in this section present examples of dosimeter responses are only approximations. Data should not be taken from them for site dosimetry programs.) As shown in this section and tabulated in Section 3.3, certain limitations inherent in each of these dosimeters have necessitated developing a combination dosimeter to provide expanded dosimetry coverage. Other passive systems and potential future passive and active systems are discussed briefly in Appendix B.

3.2.1 Nuclear Track Emulsion Dosimeters

Emulsions used in radiation dosimetry fall into two categories: nuclear track emulsions and ordinary emulsions for photographic or radiographic applications. Nuclear track emulsions permit observation of individual charged-particle tracks using a microscope.

The oldest type of passive personnel neutron dosimeter still in use at DOE facilities is nuclear track emulsion. The Kodak Personal Neutron Monitoring Film Packet, Type A (NTA), is widely used to monitor the exposure of individuals to energetic fast neutrons at DOE accelerators. In addition, boron- or lithium-loaded emulsions are commercially available for thermal neutron detection. The packet consists of a sensitive emulsion approximately 20 μm thick, bonded to a cellulose triacetate base 200 μm thick, and encased in an opaque paper wrapping. The NTA emulsion consists of silver bromide grains (approximately 3 μm thick) suspended in a gelatin-type medium. Neutrons are detected by observing the number of proton recoil tracks per unit area of film emulsion after the film is exposed, developed, and read by optical magnification. The generation of detectable proton recoil tracks

requires interaction with the emulsion of neutrons having energies greater than 0.4 to 0.7 MeV, depending on the grain size in the film and the number of grains considered to constitute a track. At lower neutron energies, few discernible tracks are produced. At greater neutron energies, if the film is properly calibrated, the dosimeter will closely approximate the dose equivalent up to an energy of approximately 3.5 MeV. At energies greater than 3.5 MeV, the film begins to overestimate the dose equivalent.

Processing

Radiation absorbed in an individual silver bromide grain forms a "latent image," which accelerates the reduction of the grain to elemental silver under the chemical action of development. Further steps are necessary to remove the undeveloped grains and make the pattern of developed grains permanent so that the dosimeter can be read out by optical means. This photographic development is a process of amplification, whereby the few silver atoms that constitute the latent image are multiplied by a factor on the order of 10^{10} until the full grain is converted to elemental silver. The latent image is defined as the physical condition of a grain: namely, the condition that permits the chemical developer more rapidly to reduce to elemental silver those grains that have absorbed radiation than those that have not. The reducing agent itself is usually one or more aromatic organic compounds. Common organic reducing agents, such as amidol or a mixture of metol and hydroquinone, all increase in activity with pH. The pH is usually established and maintained by added alkali and buffer. Because of the complexity of the developer-film system, it is general practice to use commercial developers recommended by the manufacturers for the emulsion in question. In addition to being a function of the chemical composition of the developer, the extent of development is influenced by increasing development time and temperature.

After development, the emulsion is rinsed briefly in a "stop bath," usually a dilute acetic acid solution, which stops development quickly by lowering the emulsion pH. Use of a stop bath is recommended to define the end of development with better precision than with a mere water rinse before fixation. The undeveloped silver halide is then dissolved in the fixer, or "hypo," a sodium thiosulfate solution. Finally, the emulsion is thoroughly

washed in fresh water and dried in air. The steps after development have little effect on the developed grains.

Development conditions greatly influence the apparent response of emulsions to radiation. The single most effective defense against errors from this source lies in processing calibration and personnel dosimetry films simultaneously. For greatest accuracy, however, standardized processing techniques are necessary, also. A good processing method should provide for 1) time control, 2) temperature control, 3) developer suitability and uniformity, and 4) adequate agitation of chemical processing solutions. Recommendations regarding the first three conditions are usually provided by the film manufacturer. Chemical development time should be sufficiently long that it can be controlled within a few percent. A temperature of about 20°C is usually specified; variations of 1°C can affect the number of tracks processed by a few percent. A wide variety of chemical developers is available, many of which give fairly satisfactory results on many emulsions. Since the development process is a subtle one, however, it is advisable to follow the manufacturer's selection of developer for a particular emulsion unless there are reasons to do otherwise. Sufficient quantities of developer should be prepared so that all interrelated films can be processed in the same batch of developer. The composition of developer changes with use and age; tests with calibration films will reveal the magnitude of such changes. In general, the life of a developer is prolonged if it is stored in a closed container in a refrigerator. Agitation increases uniformity of development over the full area of the film.

Although the latent image can fade, the amount of fading can be reduced by sealing the NTA film in moisture-proof packages with or without desiccants.

Readout/Interpretation

Neutron interactions leading to changes in film density on NTA film, could permit quick and easy evaluation of the response. However, because photons produce the same effect, it is difficult to determine the neutron response when photons are present. For this reason, fast-neutron monitoring is typically performed by track-counting methods.

As a means of measuring fast-neutron response, track counting depends on the hydrogen in the emulsion and in surrounding substances, including radiators. Elastic scattering of fast neutrons with hydrogen produces recoil protons. These protons lose energy to the grains in the film. The latent images formed during the passage of a recoil proton through the emulsion consist of a number of individual grains along the path of the proton. When the film is developed, the track of the proton can be seen by means of a microscope.

The tracks are counted using a dark-field microscope with a magnification of about 750X. In this device, the background of the field of view appears dark and the tracks are seen as a series of white dots. The readout method consists of counting the number of tracks in a field of view and dividing it by the area of film examined. The readout is typically given in tracks/cm^2. The field in this case is only a small portion of the entire film exposed to radiation. Therefore, the number of tracks seen in one field is small and varies from field to field. For this reason, the fields to be viewed during counting should be chosen at random and the results averaged to obtain a mean. The person counting the tracks is then less likely to influence the result. The number of fields that must be counted to obtain consistent results is a function of field size. As a rule of thumb, automatic or manual counting programs should require from 25 to 40 fields for good statistics. The counting of this large number of films may be quite tedious and labor intensive unless automated readout systems are employed.

Up to about 15 MeV, the energy transfer process in the film is predominantly through the elastic collision of neutrons with hydrogen nuclei. (Above 1 MeV, these collisions in the surrounding material, such as the wrapper, also lead to significant energy deposition by the protons in the emulsion.) This is a useful process for dosimeters since it is the same one that is primarily responsible for fast neutron dose in tissue. Above 15 MeV, nuclear reactions with the heavier elements become the primary energy transfer process. The reactions are very similar to those for high-energy protons.

For the range of neutron energies between 0.5 and 14 MeV, as Figure 3.1 shows, the number of proton-recoil tracks remains relatively independent of

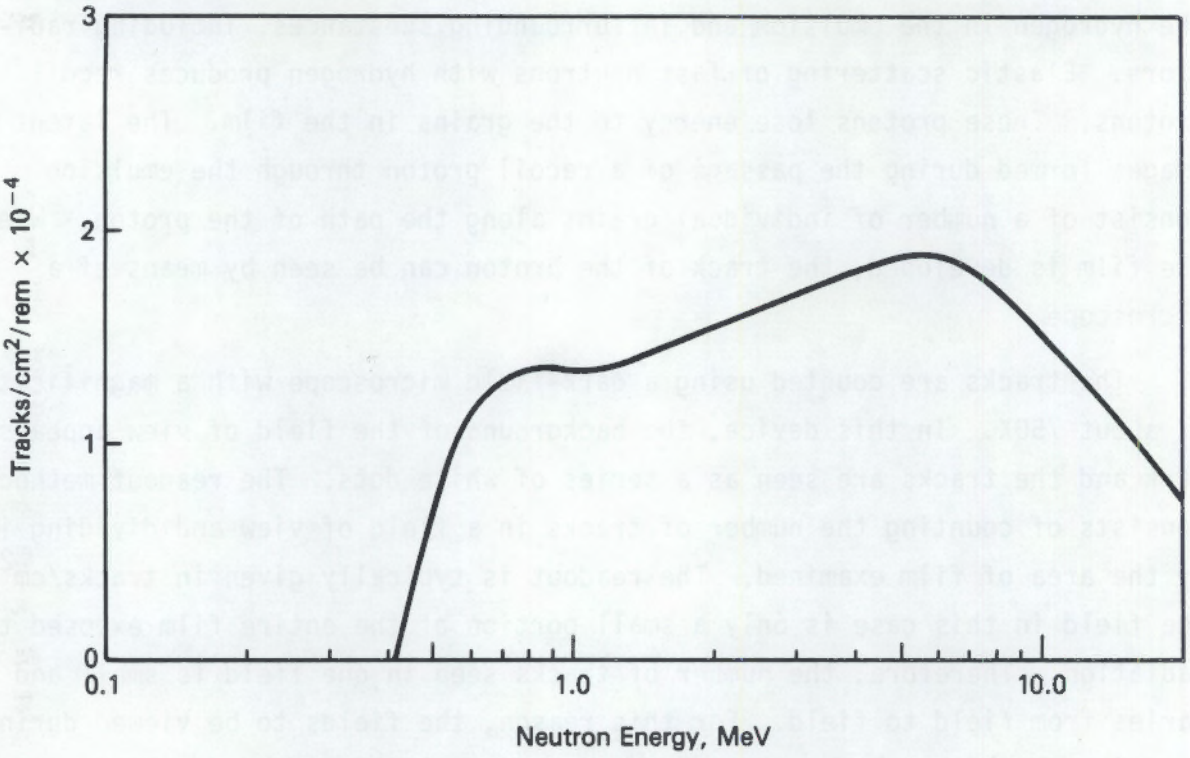

FIGURE 3.1. NTA Response Versus Neutron Energy

the neutron energy, assuming that the film had been exposed under proton-equilibrium conditions. Thus in this energy range, the dose equivalent can be evaluated fairly well since the quality factor is almost constant. However, between thermal and 0.5 MeV, this method fails and other dosimetry systems (i.e., proton recoil track etch detectors or TLD albedo dosimeters) must be employed.

An ideal dosimeter should follow variations in LET in tissue. However, photographic grains behave as discrete units. If the LET is too low, they may not be developable at all; if too high, energy exceeding the threshold may be deposited in a grain and thereby wasted. The sensitivity of the NTA film varies as a function of neutron energy; within its effective energy range, one track is produced per 1500 to 3000 incident neutrons.

Under conditions of high humidity and high temperature, fading of the latent image can occur unless special precautions are taken. Fading can be reduced by dessication or wrapping the dosimeter packet in aluminum foil

(Brackenbush et al. 1980). Because fading can be a problem, it is important to use both irradiated and unirradiated control dosimeters to assure proper dose-equivalent interpretation.

Advantages/Disadvantages

The main advantages of the NTA film dosimeter are that the film is inexpensive and responds to high-energy neutrons. It was one of the earliest neutron dosimeters in use and is fairly well characterized.

However, NTA film suffers from several disadvantages. The use of these emulsions is limited by interference from to gamma rays. The response amounts to a fogging effect, which makes it quite difficult to pick out the tracks. Thus, a gamma field that produces an exposure of about 1 rem or greater renders this type of film unreadable for neutrons. Since thermal neutrons also produce protons when capture occurs in nitrogen, the total response may contain tracks produced by these protons. However, the sensitivity to thermal neutrons is about 25 to 30 times lower than it is to fast neutrons.

In the detection of fast neutrons, the number of proton recoil tracks/cm^2 depends on the neutron energy and the emulsion wrapping. Since this dependence cannot be completely eliminated, especially at low energies, even by optimum adjustment of the wrapper composition, calibration against a known fluence of appropriate energy spectrum greatly improves accuracy. Calibration films should be processed along with the neutron-monitoring NTA film to allow an adequate interpretation of the film's response. The response of a monitoring film can be related to that of the calibration film. The fluence derived can then be evaluated in terms of a dose equivalent if the neutron spectrum to which the film has been exposed has been characterized adequately to make the comparison with the calibration film meaningful. However, this detailed information on neutron spectra in the workplace is not generally available.

Fading of the latent image may occur after it has been established, so that track density decreases with increasing time between exposure and development. Since fading may occur during the course of extended exposures, long exposures may less accurately represent absorbed dose than short exposures. Fading decreases with increasing grain size, increasing emulsion pH,

increasing specific ionization of incident particles, decreasing relative humidity, decreasing temperature, and decreasing content of oxygen in the atmosphere in contact with the emulsion. Of these influences relative humidity is dominant; fading at relative humidities less than 50% is only a small fraction of that above 80%. The track count for typical exposures to fast neutrons decreases by half in 2 to 4 weeks at a relative humidity of 33%. Half of the tracks may be lost at relative humidities in excess of 75% within two days for film without moisture-proof protection. However, it has also been shown that when film is properly dried and protected, 50% fading occurs only after periods in excess of 4 weeks. Another prominent mechanism of fading is oxidation of the latent image (especially if on the grain surface) by atmospheric oxygen; the rate is increased by high emulsion water content and low pH.

If track fading is controlled, the major disadvantages of NTA film are its energy dependence and statistical errors at low neutron doses. The response (tracks/rem) varies by a factor of 2 from 0.7 MeV to 14 MeV. Nuclear track emulsion film is also sensitive to thermal neutrons, which interact with nitrogen in the emulsion to produce protons by an N(n,p) reaction. If thermal neutrons are present, they may be excluded by sandwiching the film badge between 1-mm Cd-foils. On a dose-equivalent basis, the NTA dosimeter has about the same sensitivity to 15-MeV neutrons and thermal neutrons.

The number of tracks/cm^2 produced by an absorbed dose of 1 rad in Type A or other fast neutron dosimeter film depends on the angle of fast neutron incidence, since the relative contribution of protons from the emulsion and wrapper differ with angle of incidence. Track counts are also influenced by scattering media in the vicinity of the badge. A photographic density may be caused by mechanical abrasion, chemical reactions, light, and elevated temperature, as well as by exposure of the emulsion to the radiation of interest. Sensitivity may be affected by emulsion temperature at the time of exposure and the by environmental humidity. At room temperature, however, this source of error is not significant.

3.2.2 Thermoluminescent Dosimeters

Thermoluminescent dosimeters emit light when heated after being irradiated by ionizing radiation. This phenomenon occurs in many minerals found in nature. For neutron dosimetry, special phosphors containing lithium, calcium, or boron are made. The lithium or boron absorbs neutrons and produces charged particles that interact with the phosphor.

The dosimeter most widely used at DOE facilities is the TLD-albedo dosimeter, which uses the $^{6}Li(n,\alpha)^{3}H$ reaction in thermoluminescent materials to detect neutrons. Lithium has a cross-section that is inversely proportional to the neutron velocity or the square of the neutron energy. Thus, it is very sensitive to thermal neutrons but relatively insensitive to fast neutrons. Thermoluminescent-albedo dosimeters are worn on the body. Incident fast neutrons enter the body, lose energy through moderation, and some are reflected back to the dosimeter (hence the term albedo, from the reflected neutrons). Slow neutrons interact with the thermoluminescent material more effectively than fast neutrons, usually through $^{6}Li(n,\alpha)^{3}H$ reactions. The charged particles (α and ^{3}H) excite the thermoluminescent material. When heated, the phosphor emits light in quantities proportional to the energy deposited in the material by neutron exposure.

The thermoluminescent material is sensitive to both neutrons and photons, so a correction must be made for gamma exposures by using matched pairs of TL chips. One chip is made from ^{6}LiF, which detects neutrons and photons, and the other is made from fully enriched ^{7}LiF, which detects photons almost exclusively. The neutron response is found by subtracting the ^{7}LiF response from the ^{6}LiF response.

The TLD-albedo dosimeter must be worn close to the body to function properly since the albedo process depends on scatter from the body. As it is moved away from the body, its sensitivity to fast neutron decreases, whereas its sensitivity to thermal neutrons remains constant. The common practice of wearing a dosimeter loosely clipped on a pocket containing a pack of cigarettes can cause inaccurate readings. Some TLD-albedo dosimeters will not function properly if they are worn backwards, clipped to the inside of a pocket, or loosely held on a necklace.

There are also other TLD techniques that are less widely used. The TL material can be intimately mixed with a hydrogenous material to measure the dose from recoil protons; however, gamma rays can interfere with the interpretation of this dose. In deep-trap TLDs, neutrons and other high LET particles can interact with the phosphor to activate different traps in the TLD, which produce peaks at different temperatures upon readout. Fading is also a problem in most of the deep-trap TL materials that are currently available.

Processing/Readout/Interpretation

It is difficult to establish a demarcation line between processing and readout/interpretation of thermoluminescent dosimeters. Therefore, both categories will be discussed jointly in this section.

TLD-600s are usually used for measuring neutron exposure. TLD-10D, 600, and 700 are produced by homogeneous melting of lithium fluoride, magnesium fluoride, lithium cryolite, and lithium titanium fluoride, resulting in a phosphor containing 300 ppm of magnesium and 10 to 20 ppm of titanium. A single crystal is solidified from the melt, then pulverized; the powder grains are sieved and separated; and the TLD chips are produced. The isotopic compositions of these TLDs are given in Table 3.1. Gamma interference in TLD-600 is typically less than other TLD types. The thermal neutron response of ^{6}LiF per rem is about 40 to 60 times greater than from those of gamma. The response of LiF TLD-600s as a function of incident neutron energy when worn near the body or placed on a phantom is shown in Figure 3.2. A normalized ICRP dose equivalent conversion curve is shown in Figure 3.3 for comparison.(a)

TABLE 3.1. Isotopic Constituents of Harshaw TLD-100, 600, and 700

Phosphor Type	^{6}Li, %	^{7}Li, %
TLD-100	7.5	92.5
TLD-600	95.6	4.4
TLD-700	0.01	99.99

(a) This curve is adapted from a 1982 private communication from R. V. Griffith and T. McMahon, Lawrence Livermore National Laboratory, Livermore, California.

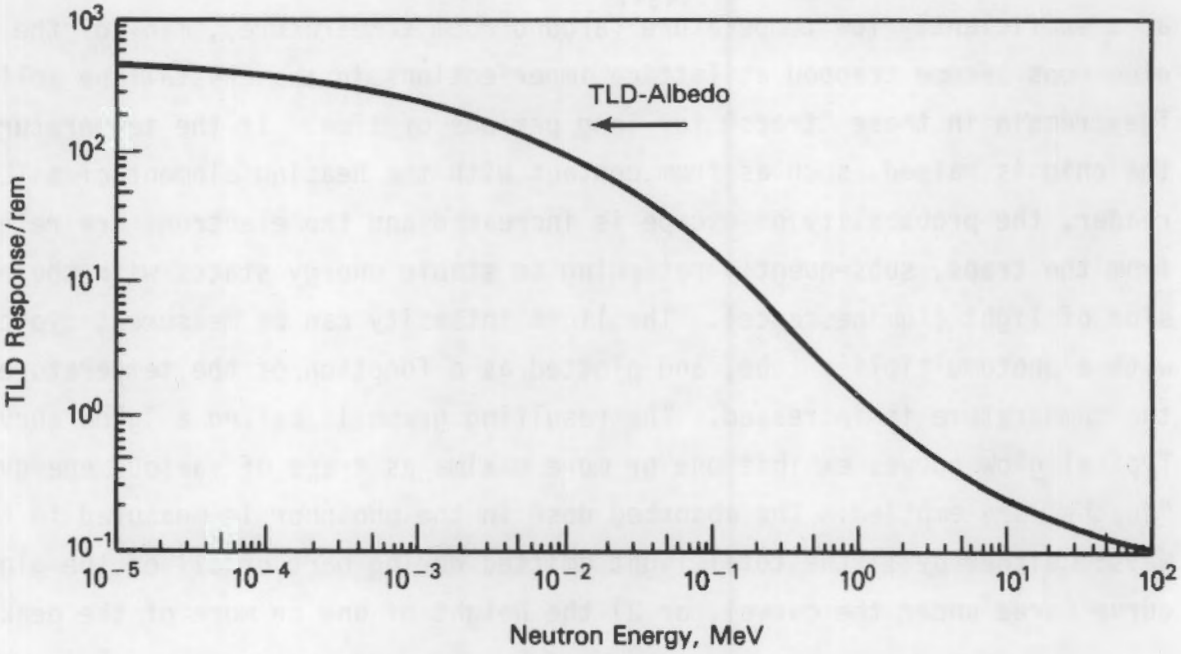

FIGURE 3.2. LiF TLD-600 Neutron Energy Response

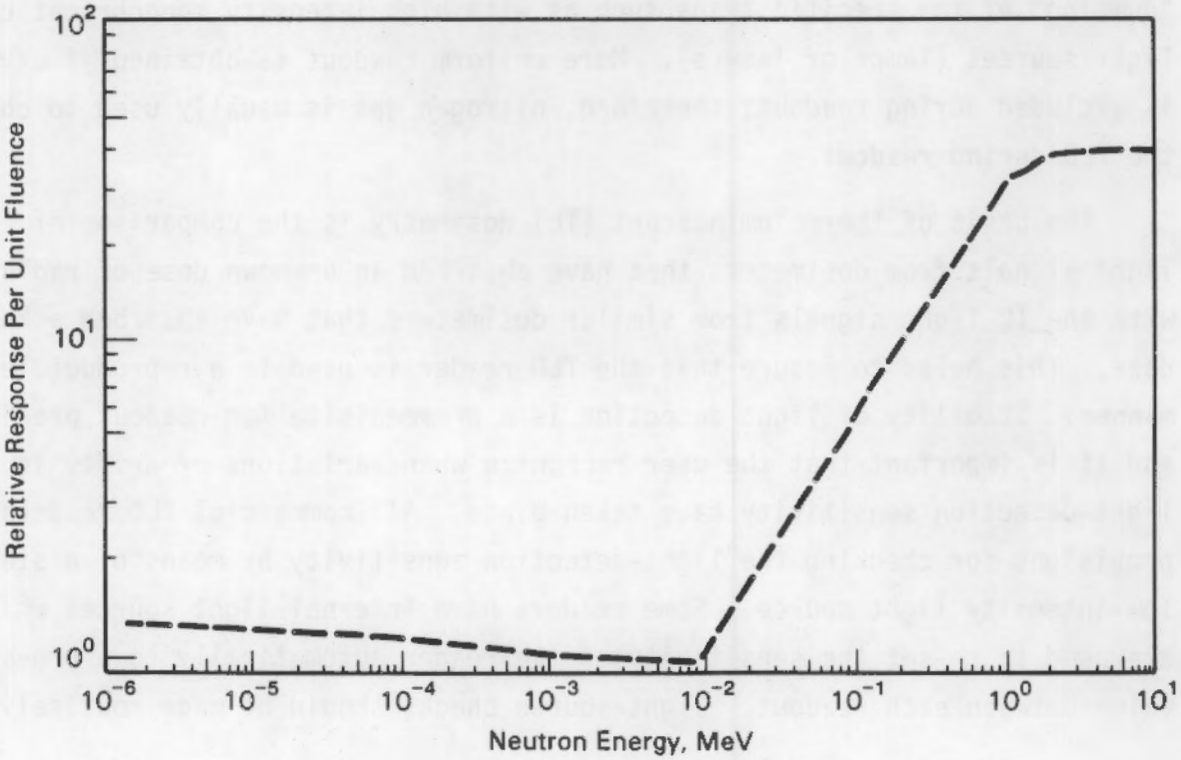

FIGURE 3.3. Normalized ICRP Dose Equivalent Conversion

When a thermoluminescent phosphor is exposed to ionizing radiation while at a sufficiently low temperature (around room temperature), many of the freed electrons become trapped at lattice imperfections in the crystalline solid. They remain in these "traps" for long periods of time. If the temperature of the chip is raised, such as from contact with the heating element of a TLD reader, the probability of escape is increased and the electrons are released from the traps, subsequently returning to stable energy states with the emission of light (luminescence). The light intensity can be measured, typically with a photomultiplier tube, and plotted as a function of the temperature as the temperature is increased. The resulting graph is called a "glow curve." Typical glow curves exhibit one or more maxima as traps of various energy "depths" are emptied. The absorbed dose in the phosphor is measured in two ways: either by 1) the total light emitted during part or all of the glow curve (area under the curve), or 2) the height of one or more of the peaks.

Heating of TLD chips may be accomplished by any one of the following heating methods: 1) ohmic, 2) hot nitrogen gas, 3) radiofrequency, or 4) radiant heat. Readout may also be accomplished by optically stimulated "dumping" of the specific traps such as with high intensity monochromatic light sources (lamps or lasers). More uniform readout is obtained if oxygen is excluded during readout; therefore, nitrogen gas is usually used to cover the TLD during readout.

The basis of thermoluminescent (TL) dosimetry is the comparison of TL light signals from dosimeters that have absorbed an unknown dose of radiation, with the TL light signals from similar dosimeters that have absorbed a known dose. This helps to insure that the TLD reader is used in a reproducible manner. Stability of light detection is a prerequisite for readout precision and it is important that the user recognize when variations or drifts in the light-detection sensitivity have taken place. All commercial TLD readers have provisions for checking the light-detection sensitivity by means of a stable, low-intensity light source. Some readers have internal light sources which are used to re-set the sensitivity of the reader automatically to a pre-set value between each readout. Light-source checks should be made routinely

before and after measurement sessions according to the manufacturer's recommendations. Any necessary adjustment can be made to the reader sensitivity, or a correction factor calculated and applied to subsequent readouts. However, other uncertainties can also arise:

1) variations in the reflectivity of readout trays--caused by burnt surface dust, or oxidation
2) variations in the lateral positioning of dosimeters on the tray--avoided if appropriate depression is provided
3) variations in TL self-absorption and scattering--caused by differing thicknesses of the dosimeter. This is especially important for the comparison of TL readouts obtained by irradiation with high LET radiation and with low LET radiation.

Phosphors used in TLDs may suffer from fading. If the deeper energy traps in the solid are used, the fading is less severe. For those substances with glow peaks above about 200°C, the fading becomes much less severe. If the main peak in LiF is used primarily for dosimetry purposes, the stored signal does not fade severely at room temperature. Many phosphors respond to normal ambient levels of ultraviolet and visible radiation. The effects are twofold: the production of a light-induced TL signal, and the phototransfer and subsequent retrapping of charge carriers. In some phosphors the latter effect can result in increased fading of the dosimetry traps, while in others a transfer of electrons to the dosimetry traps results in an apparent increase in the subsequently recorded TL signal. The packaging of dosimeters in light-tight envelopes minimizes these effects. Ambient lighting levels, especially from fluorescent lights, should be reduced in areas where dosimeters are handled or processed outside their protective envelopes. Care should be taken to ensure that in storage and use, dosimeters are not heated much above normal ambient temperature.

All phosphors display some changes in their thermoluminescence, depending on the thermal treatment which they receive. To ensure complete readout of the stored signal and repeated use of the phoshor without significant change in its thermoluminescent sensitivity, a thermal anneal is required before

re-use. Before making radiation measurements, all dosimeters should be identically annealed, as far as is practical, to standardize their sensitivities and backgrounds. Annealing is especially important in order to remove residual TL signals, to establish the TL sensitivity, and to eliminate unstable low-temperature glow peaks. This technique also reduces the effects of spurious phosphorescence and thermoluminescence induced by ambient ultraviolet radiation and visible light. Although individual dosimeters may be annealed in the reader, when a long-term anneal is required or many dosimeters have to be annealed, an external annealing oven may be more convenient. Most TLD equipment manufacturers supply suitable ovens as approved accessories to their readout systems. Some of these ovens are of the fan-assisted hot-air circulation type. This heating method ensures a rapidly achieved uniformity of temperature through the entire volume of the oven, and hence a reduction of temperature gradients in the dosimeters. Ovens should be kept scrupulously clean, and, preferably, should be used for only one type of phosphor to prevent cross contamination and intermixing.

Advantages/Disadvantages

TLD-albedo dosimeters have a number of attractive features. They always give some indication when exposed to a significant neutron dose, are relatively inexpensive, and can be reused. In addition, they are easily fabricated and are usually lightweight and easy to wear. Readout is simple and can be automated. It is possible to process several thousand dosimeters with relative ease. Finally, they are relatively insensitive to humidity and moderate mechanical shock.

The single most important disadvantage of TLD-albedo dosimeters is that their sensitivity is highly dependent upon the energy of the incident neutron. The dose equivalent indicated by the dosimeter can be in error by a factor of 10 if the dosimeter is not properly calibrated. The TLD-albedo dosimeter is also gamma-sensitive. In mixed radiation fields, care must be taken to properly subtract out the photon response of the ^{6}LiF chip. The readout process anneals the chips thereby erasing the record. Therefore, thermoluminescent dosimeters do not give a permanent record, as film or track etch dosimeters do. If the TLD reader malfunctions, the reading may be lost. Even though

each thermoluminescent dosimeter is individually calibrated before use, each must be carefully annealed to preserve the accuracy of its calibration.

3.2.3 Proton Recoil Track Etch Dosimeters

Certain plastics are sensitive to charged particle interactions in which the interaction causes submicroscopic damage to the plastic. Neutrons interact with hydrogen in the specialized plastics or radiators, producing recoil protons with high elastic scattering cross sections. Preferential etching of these damage sites by a strong basic solution may result in tracks that are visible under a microscope.

Plastics used to detect neutrons in this way are called track etch detectors or TEDs. Materials such as lexan, polycarbonate, cellulose nitrate and LR115 have been used as neutron track detectors, but the most sensitive over a wide neutron energy range is the polymer of allyl diglycol carbonate, known as CR-39, the monomer of which is produced by PPG Industries, Pittsburgh, Pennsylvania. Radiation damage in polymers involves scission of the molecular chains. The CR-39 polymer is superior to other track detectors because it is highly sensitive to chain scission from radiation interaction, has a dense, uniform molecular structure, and is optically transparent facilitating readout. The CR-39 responds to alphas, protons, neutrons, and heavy charged particles. It has a low-LET threshold, a large energy range, and a good minimum sensitivity. Although hydrogen recoil is the primary mechanism of neutron interactions with the highly crosslinked polymer, CR-39 is also sensitive to (n,α) reactions, heavy recoil reactions at high energies, and breakup reactions of carbon $(n,3\alpha)$ and oxygen $(n,4\alpha)$.

Because of the short range of hydrogen recoils, the tracks produced by chemical etching require high magnification. However, the site of the recoil tracks can be enlarged by electrochemical etching. High electric fields cause electrical breakdown at the tips of the tracks, and very vigorous etching occurs. The relatively large tracks (tens of micrometers in diameter) formed are visible under low magnification. The technique is sufficiently accurate that a growing number of DOE laboratories and commercial dosimetry vendors are using it for neutron dosimetry.

The CR-39 foils being used at DOE facilities are made of a high-purity "dosimetry grade" CR-39 monomer. The readily available technical grade CR-39 is not adequate for personnel neutron dosimetry. The "dosimetry grade" CR-39 sheets average 25-mil thick and vary little in thickness over the sheet (approximately ±2 mil). The sheets are covered on both sides with a nominal 5-mil thickness of polyethylene, which is required to protect the foil from radon alpha particles and abrasion, as well as acting as a recoil proton radiator.

Processing

When the CR-39 polymer is chemically etched with a caustic solution, fragments of the broken bond are selectively extracted. This chemical change results in the formation of a pit in the material. However, chemically etched, charged-particle tracks produced by neutrons below about 250 keV are at or below the size limits of resolution of optical microscopes. Electrochemical etching (ECE) makes it possible to enlarge these damaged tracks to a macroscopic size. Enlargement involves stressing the track detector by applying alternating-current electric fields across the foils during chemical etching. Once the pit has been formed, the electric field at the tip of the track is much greater than the average electric field applied to the undamaged surface. Very high, localized stress gradients can begin electrically breaking down the surface, resulting in a damage pattern in the shape of a tree at the pit site. The pits can then be detected and related to neutron dose by optical readout techniques.

There are different ways to chemically process the irradiated CR-39: 1) "hot" chemical etch, 2) "hot" chemical etch followed by room-temperature electrochemical etch, and 3) "hot" electrochemical etch. Each of these processes has its own advantages; however, the hot electrochemical etch provides superior energy response and optical counting characteristics. A "hot" (60°C), low-frequency (60 Hz) ECE procedure is recommended to improve the energy dependence. The details of a "hot" processing procedure for electrochemical etching of CR-39 are given in Appendix D.

The chemical etchant concentration and the etching temperature influence the size of the tracks. Good track development requires that the etching

rate of the track, V_t, exceed the etching rate of the bulk material, V_b. The structure of highly crosslinked polymers such as CR-39 helps to decrease the V_b. The track length, L, and diameter, D, depend on the difference in V_t and V_b. Track registration is also dependent on the length of chemical etching. Insufficient etching time does not produce visible tracks. Too much etching time enlarges the diameter to the point that discriminating track from background is difficult or impossible. The most desirable etchant, then, would selectively etch only at the liquid-solid interface, dissolving the debris of lower molecular weight produced by charged particles. High-normality solutions of KOH or NaOH are typically used as the etchant.

Processing parameters that have a significant effect on the size and number of tracks (track density) are the etching solution concentration, etching duration, temperature, voltage (electric field strength), and frequency. These parameters given below should be generally applicable but they should be verified or determined for each user. Consistency in processing parameters is important for achieving a high degree of precision and accuracy.

The KOH or NaOH etchant used in processing has a normality of 6 to 7. The duration of the etch may vary from 2 to 5 h at a frequency of 60 Hz with an additional high frequency ("blow up") step at 2000 Hz to increase the size of the tracks. Typically, longer etch times yield larger track densities. The chemical etch rate is very slow at ambient temperatures but increases rapidly with temperature. The etching process is typically performed at around 60°C. The oven used should be maintained to within ±0.5°C for processing precision and needs forced air circulation to keep the temperature uniform throughout the oven when more than one processing chamber is used.

The voltage used is selected for optimization of response. Track density increases with voltage to an optimum between about 2500 and 3500 volts for a sample thickness of about 25 mil. The background rises faster than signal track density so a compromise must be made to keep the lower detection limit at an acceptable level. Variations in sample thickness also must be considered. Track density varies by about 1% per mil of sample thickness from the 25-mil average. Thicker foils reduce the electric field strength, resulting in smaller and fewer detectable tracks for the same applied voltage.

Thin foils have a higher field strength. The result is larger tracks and a higher track density. These variations must be considered in the evaluation of dose equivalents.

Standard foils exposed to a known neutron fluence and energy should be included in each etch chamber to aid in the evaluation of neutron dose.

Readout/Interpretation

The energy dependence of CR-39 foils using electrochemical etching (ECE) is superior to that of albedo neutron dosimeters or that of CR-39 using chemical etching alone. The CR-39 dosimetry system does not have the severe energy dependence that exists with albedo neutron dosimeters exposed to fast neutrons or the fading and reading problems encountered with NTA film. One of its biggest advantages is that it works independently of the albedo effect. It detects neutrons within the energy range from about 100 keV to >18 MeV and probably can be extended to the thermal neutron range if boron- or lithium-loaded radiators are used in conjunction with it. Using a "hot" ECE, the energy response to neutrons (Figure 3.4) is fairly flat from about 150 keV to 3.5 MeV, but drops by about 40% above 4 MeV. The sensitivity of the dosimetry system varies from 1.5 to 9 tracks/cm^2/mrem (depending upon the processing), with a background equivalent to 5 to 10 mrem for new CR-39 foils. The minimum sensitivity is 5 to 10 mrem depending upon the neutron energy and background of the CR-39 material.

The standard readout technique for CR-39 dosimeters is to use an optical microscope, together with an image analyzer to determine the track density for a certain field size. Microfiche readers are also used with an operator manually counting the number of tracks per field size. This is a tedious operation and is not recommended for large dosimetry programs. For large dosimetry programs, the output from the optical microscope should be automated. Enough fields of view should be read to give a representative number of tracks. Typically, samples are read along the center of the sample, avoiding the edges (boundaries) of the ECE portion.

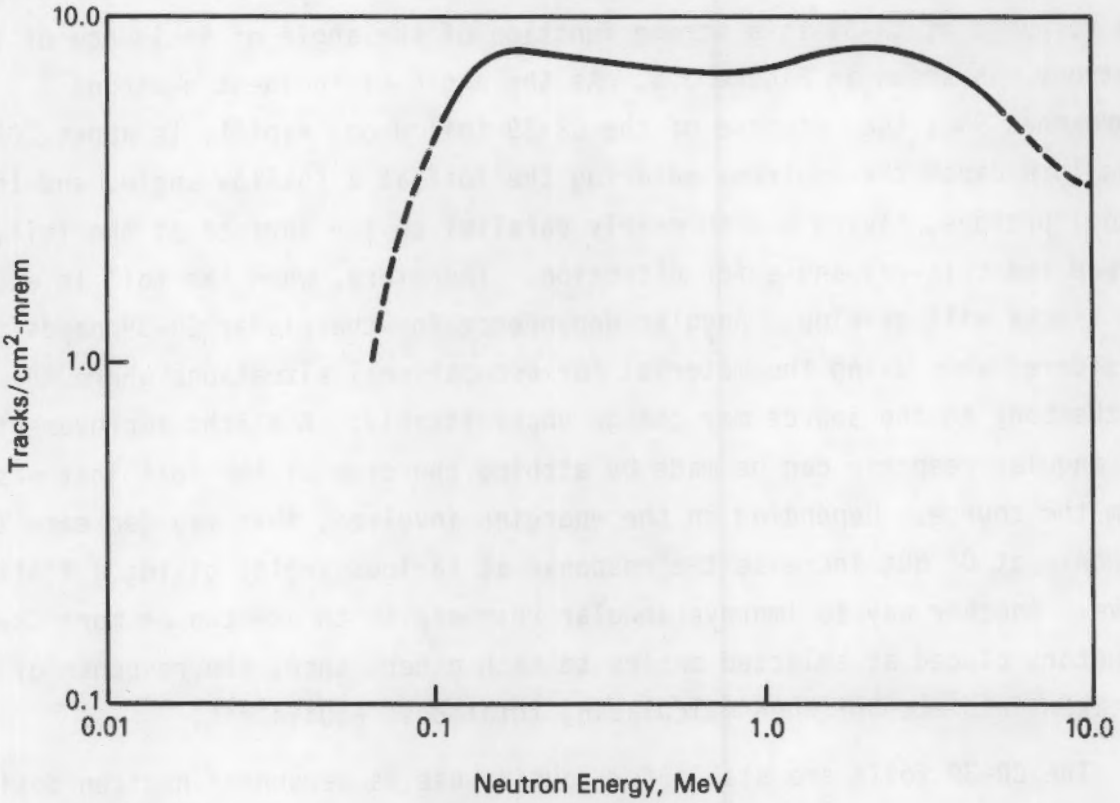

FIGURE 3.4. Energy Dependence of CR-39 Personnel Neutron Dosimeters Using "Hot" Electrochemical Etching

Advantages/Disadvantages

These recoil track detectors have the advantages listed for fission fragment recoil track detectors in Appendix B, Section 1.1, with none of the attendant fission foil problems. These advantages are:

- well-defined energy response
- insensitivity to beta and gamma radiations
- stability in humidity and temperature to 50°C
- accuracy to ±25% at 10 mrem
- a lower limit of useful range of 10 mrem between 100 keV and 18 MeV.

The main difference is that with proton recoil-track dosimeters the tracks are smaller than fission fragment tracks, making them more difficult to count visually.

The major disadvantage of CR-39 dosimeters is their angular dependence. The response of CR-39 is a strong function of the angle of incidence of the neutrons, as shown in Figure 3.5. As the angle of incident neutrons approaches 90°, the response of the CR-39 foil drops rapidly to about 20%. This is because the neutrons entering the foil at a shallow angle, and the recoil protons, having a path nearly parallel to the surface of the foil, exceed the critical angle for detection. Therefore, when the foil is etched, few tracks will develop. Angular dependence for the planar CR-39 needs to be considered when using the material for occupational situations where the angle of the body to the source may change unpredictably. A slight improvement in the angular response can be made by etching the side of the foil that was away from the source. Depending on the energies involved, this may decrease the response at 0° but increase the response at various angles giving a flatter curve. Another way to improve angular response is to use two or more CR-39 detectors placed at selected angles to each other; then, the response of each is taken into account when calculating total dose equivalent.

The CR-39 foils are stable for routine use as personnel neutron dosimeters. As long as the CR-39 foils are protected from light and temperatures above 50°C, fading is negligible. The CR-39 foils are damaged, however, by UV light or prolonged exposure to high temperatures. If care is taken to protect the foils from light or excessive heat, unexposed foils are useable for at least one year. However, it is suggested that the CR-39 foils be issued for no longer than a six-month exchange period, because the background track density on the foils will be increased by the environmental neutron background with a resulting increase in minimum detectable levels. To keep the background of the CR-39 foils as small as possible, only relatively new foils should be issued. Exposure to alpha particles (radon gas, etc.) can also increase the background, so the detecting surface must have a protective layer sufficiently thick to absorb high-energy alpha particles and prevent contamination.

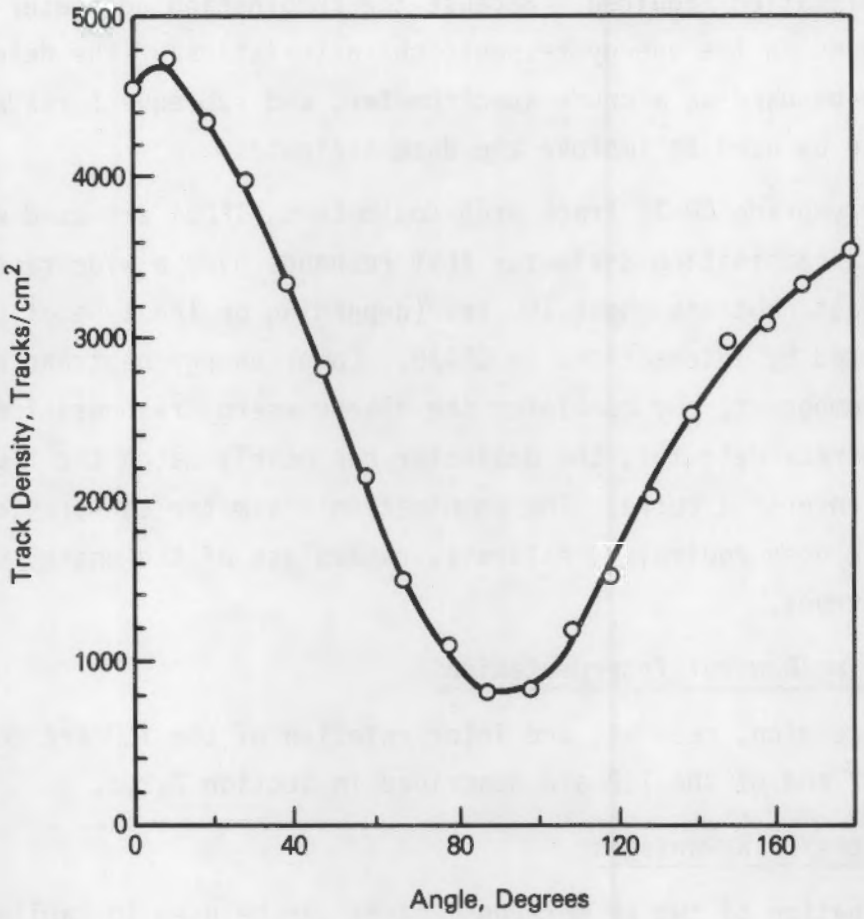

FIGURE 3.5. Directional Response of CR-39 Foils in Air

Currently, the processing of CR-39 is a labor intensive process; however, improvements in the equipment, procedures, and material are expected to reduce the time and effort required for processing.

3.2.4 Combination Dosimeters

Two or more detectors can be used in a single dosimeter so that the advantages of each component (energy response, sensitivity, directional response, etc.) are combined to provide a dosimeter that is superior to one based on a single element. The combination dosimeter concept was initially conceived by R. V. Griffith of LLNL and described in various DOE neutron workshops. The detectors chosen for the combination dosimeter being used in DOE facilities

are the TLD-albedo and one or more track detector materials, depending on the specific application required. Because the combination dosimeter makes use of the differences in the energy response characteristics of the detector components, it can be used as a crude spectrometer, and subsequent readout of each component can be used to improve the dose estimates.

Dosimetry-grade CR-39 track etch dosimeters (TEDs) are used with TLD 600s and 700s as a combination dosimeter that responds over a wide range of energies. Fast neutrons above 100 keV (depending on the type of processing) can be detected by interactions in CR-39. Lower energy neutrons are detected by the TLD component. By combining the albedo energy response function with that of the track detector, the dosimeter can nearly match the fluence-to-dose equivalent conversion curve. The combination dosimeter can provide a much more accurate dose equivalent estimate, regardless of the energy of the incident neutrons.

Processing/Readout/Interpretation

The processing, readout, and interpretation of the TLD are described in Section 3.2.2 and of the TED are described in Section 3.2.3.

Advantages/Disadvantages

A combination of two or more dosimeters can be used to capitalize on the advantages of both. This can be essential in those areas where the useful energy range of the individual dosimeters is inadequate for actual conditions. Other advantages include greater accuracy, a decreased lower limit of detectability, and less energy dependence. Additional information is provided concerning the neutron energy spectrum that may be critical in converting absorbed dose data to dose equivalent. Major disadvantages include the cost of two evaluation systems (TLD and recoil track) and the angular dependence of both types of detectors. As with all types of neutron dosimeters, care is required in the calibration and evaluation of combination dosimeters. Moderate cost and energy response characteristics make this dosimeter type most applicable in environments where workers must be monitored for a wide range of neutron energies.

3.3 SUMMARY OF DETECTOR CHARACTERISTICS

There are several radiation detectors that can be incorporated into neutron dosimeters, but only the three described above are presently used within DOE passive dosimetry systems. For those persons likely to be exposed to neutrons, the energy range is the primary concern in selecting the best dosimetry system. As shown in Figure 3.6, one or more detectors can be chosen for the neutron energy in the work place. If the maximum energy expected requires the use of a TED or NTA, a TLD will be required also to measure dose from thermalized neutrons.

Other characteristics of the work environment and dosimetry requirements that can influence the choice of detectors are summarized in Table 3.2.

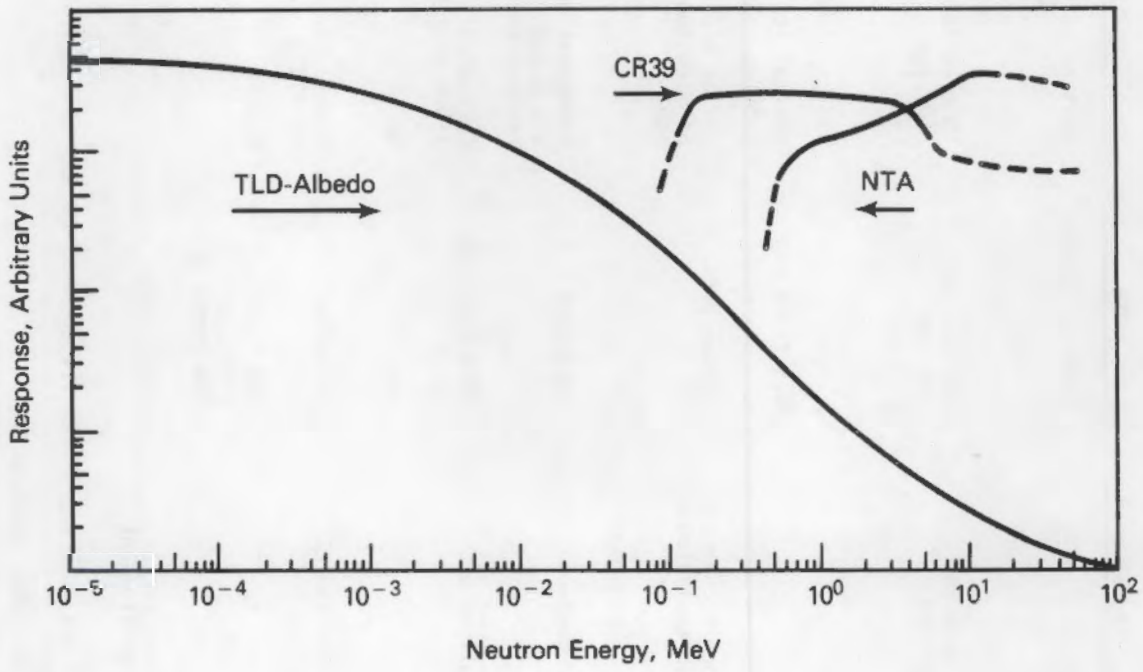

FIGURE 3.6. Energy Response of Currently Used Neutron Detectors

TABLE 3.2. Characteristics, Passive Dosimeter Systems

Characteristics	Ideal	NTA	TLD	TED	TLD/TED
Accuracy	10% at 10 mrem	100% at 50 mrem	100% at 50 mrem	25% at 10 mrem	100% <200 keV 25% 200 keV to 2 MeV
Dose Equivalent Range	10 mrem to 1000 rem	~50 mrem to 100 rem	10 mrem to >100 rem (SRP)[a]	10 mrem to >400 rem	50 mrem to 1000 rem, to <150 keV 10 mrem to 400 rem, 100 keV to 18 MeV
Useful Energy Range	All	0.5 to 14 MeV	Thermal to 1 MeV	150 keV to 18 MeV	Thermal to 18 MeV
Energy Dependence Within Useful Energy Range	Proportional to dose equivalence	Varies 200%	Varies 3 orders of magnitude (OM)	Varies 40%	Factor of 40 (thermal to 200 keV) 100% 100 keV to 18 MeV
Angular Response	Independent	Dependent	Dependent upon angle and neutron energy	80% loss of sensitivity at 90°	Dependent upon angle and neutron energy
Gamma Interference	Negligible	100% at 1 rem	Corrected (100% at 1 MeV)	Negligible	Corrected/ Negligible
Readout Repeatable	Yes	Yes	No	Yes	No/Yes
Temperature Sensitivity	Stable for EC[b] at 0 to 45°C	Unstable	Stable for EC at 100°C	Stable for EC at 50°C	Stable for EC at 50°C
Humidity Sensitivity	Stable for EC at 90%	50% loss in 2 days at 75% humidity	Stable	Stable	Stable
Ultraviolet Sensitivity	Stable for EC to environment	Sensitive	Sensitive[c]	Sensitive[c]	Sensitive[c]

(a) Up to 1000 rem for 1 MeV, but supralinearity corrections may be required.
(b) EC = exchange period.
(c) Unless shielded by dosimeter construction.

4.0 PROCEDURAL REQUIREMENTS

Occupational neutron exposure limits are presented in Table 4.1. The values for the yearly whole-body dose equivalent standard are based on the requirement that the whole-body internal dose commitment from radionuclides for which the whole body is the critical organ be combined with the external whole-body dose. Where both the external penetrating dose (including neutron) and internal dose to the critical organ are known, they shall be combined for that organ.

In order to ensure that these limits are being complied with and that the dosimetry data being collected and compared to the standards are adequate, the following procedural requirements should be followed.

TABLE 4.1. Radiation Protection Limits for Occupationally Related External and Internal Exposures

Type of Exposure	Exposure Period	Dose Equivalent (Dose Commitment, rem)
Whole body, head and trunk, gonads, lens of the eye, red bone marrow, active blood-forming organs	Year	5
	Calendar quarter	3
Unlimited areas of the skin (except hands and forearms). Other organs, tissues, and organ systems (except bone)	Year	15
	Calendar quarter	5
Bone	Year	30
	Calendar quarter	10
Forearms	Year	30
	Calendar quarter	10
Hands and feet	Year	75
	Calendar quarter	25

4.1 MONITORING

Adequate measurements and records of radiation exposure are an important part of any radiation protection program. The types and energies of radiation present in DOE facilities and the dosimetry information required dictate the

type of dosimeter needed to insure adequate measurements. This dosimetry information becomes part of the individual's exposure record.

The recommended types of personnel dosimeters are the TLD, TED, or combination TLD/TED systems. For special cases such as the measurement of high-energy neutron dose at accelerators, NTA film (or a combination that includes NTA film) might be preferred. The combination system is preferred where the neutron spectra include significant thermal, intermediate, and fast-neutron components. Existing combination TLD/TED for both whole-body and extremity measurements provide more accurate, sensitive measurements than film-based or TL dosimeters alone in the presence of the radioactive materials expected in DOE facilities. The use of neutron-to-gamma ratios should not be condoned without supporting evidence that such ratios change little with time and location.

Neutron monitoring is required where the potential exists for the individual to receive a neutron dose or total dose commitment in any calendar quarter in excess of 10% of the quarterly limits given in Table 4.1. In addition, an individual under age 18 shall neither be employed in, nor allowed to enter, controlled areas in such a manner that he or she will receive doses of radiation in amounts exceeding one-tenth of the standards. However, neutron dose to students under age 18 exposed to radiation during educational activities shall be permitted up to 0.1 rem/yr. This exposure shall be considered a part of the 0.5-rem/yr limit for workers under age 18 and not supplemental to it.

4.2 WEARING OF DOSIMETER

The normal position for wearing the dosimeter shall be prescribed by the facility personnel responsible for management of the radiation protection program. The unique characteristics of each dosimetry system and work situation determine how it should be used.

Albedo neutron systems usually require close body contact at all times during use. Sizable errors can occur if close body contact is not maintained. Albedo neutron dosimeters should have a means of maintaining this close contact with the body. For example, a requirement for close dosimeter-body contact

precludes wearing the dosimeter loosely on a chain around the neck. When guidance is not provided, usually the best approach is to attach the neutron dosimeter to the outside of the outermost layer of clothing, midway between the neck and waist on the front of the body, with the face (front) of the dosimeter oriented away from the body. For an albedo neutron dosimeter, this allows the body to serve as a moderator for the neutron flux and permits subsequent detection of neutrons by the TL chips or other albedo detector.

If there is a significant likelihood that the dosimeter will become contaminated, the dosimeter should be protected by wearing it on the inner pair of protective coveralls or covering it with protective plastic. If this is done, the plastic may modify the dosimeter response slightly, requiring the dosimeter to be calibrated under similar conditions.

For unique or unusual potential exposure conditions, additional dosimeters should be placed to reflect the maximum hazard to the trunk section of the body should be provided. This may become especially important if the dosimetry system being used is highly dependent on the angle of exposure. For example, in some specific work locations where the source of radiation is oriented in some unusual manner, some part of the head or trunk may receive a substantially higher dose than other parts of the body. Therefore, either additional dosimeters should be used or the primary dosimeter should be relocated. In such cases, the location of the dosimeter should be determined by operational health physics, approved by a supervisor, and entered in the worker's records.

4.3 EXCHANGE PERIOD

Selection of the dosimeter-exchange period shall be made so that the loss of dosimeter response or fading over the entire dosimetry period is not more than 50% at a nominal dose equivalent in excess of 0.5 rem, i.e., dose "missed" by high threshold and frequent exchanges. If the dosimeter has a lower detection limit of 50 mrem, monthly changes could result in as much as 600 mrem/yr being missed in the worst case. The exchange period should be monthly to quarterly, based on facility experiences. When guidance is not provided or

dose-tracking/dosimeter-fading studies have not been performed, a monthly exchange period is recommended.

4.4 DOSE EQUIVALENT EVALUATION

To determine the dose equivalent for most neutron dosimeters, it is necessary to apply an algorithm which incorporates several weighting factors to the dosimeter response. These factors are based upon the response or dependence of the dosimeter as a function of energy (spectrum), the angular or directional response of the dosimeter to off-normal incidence radiation, and the quality of the radiation (quality factor).

4.4.1 Energy Dependence

Most dosimeters are sensitive to neutrons over a limited energy range. Even within this range, their response is dependent upon the neutron energy and the response may vary by several orders of magnitude. Large errors can result if the energy dependence is ignored. Therefore, the energy dependence of each type of dosimeter must be determined and considered when interpreting the dosimeter response to a neutron-radiation field.

Specific energy-dependence information on each type of dosimeter is given in Section 3.

4.4.2 Angular Dependence

If a dosimeter is to be used in a "field" orientation relative to the source which is different from that used during primary calibration, correction factors should be developed relating to the angular response of the dosimeter.

For each dosimeter design and for each type of neutron radiation, the dosimeter performance for nonperpendicular incident radiation should be determined. One procedure for determining the angular dependence is to mount the dosimeters on the front face of the phantom with the angle of incidence varied in two planes perpendicular to each other. The angular response should be determined for least at seven different angles of incidence from -85° to +85°, including 0° (perpendicular incidence), in each of the two planes. Values for the dose equivalent for each irradiation exposure should be approximately

500 mrem. For a given angle of incidence and for a type and energy of incident radiation, the results of the angular dependence should be expressed as the ratio of the dose equivalent measured at the angle of incidence to the dose equivalent obtained at a perpendicular incidence. The information obtained can then be used in conjunction with a time-in-motion study of different workers to correct the dosimeter response for actual worker orientation with respect to the neutron fields present. However, in practical operations workers are exposed to a wide variety of sources ranging from nearly isotropic sources, e.g., glovebox contamination, to a beam from a source within a glovebox. Although personnel neutron dosimeters exhibit directional dependence, it would be technically acceptable to circumvent this dependence by using three perpendicular detectors. Alternatively, from the known directional dependence, adjustments can be made for other exposures, such as isotropic, perpendicular, or edge-on.

Specific information on angular dependence for each type of dosimeter is given in Section 3.

4.4.3 Dose Equivalent Conversion Factors/Quality Factors

The exposure limits specified in Table 3 are expressed in terms of rem, which implies that the absorbed dose (expressed in rad) should be multiplied by an appropriate weighting factor (quality factor) to obtain dose equivalent (expressed in rem). The quality factors to be used for determining fast neutron (>10 KeV) exposures from known energy distributions are given in Table 4.2.

The usual procedure is to determine the dosimeter response per rem as a function of neutron energy. Thus, the quality factor is "hidden" in the dosimeter response and not calculated separately. The TEPC allows separate calculation of absorbed dose and quality factors, or these quantities can be calculated from spectral measurements.

Spectral information should be used to determine a specific Q value. If the spectrum is not known, the mean value of quality factor ($\bar{Q}$ = 10) must be used. The values of Q are being reviewed, with an increase by a factor of 2 probable.

TABLE 4.2. Quality Factor Values [a]

Neutron Energy, MeV	Quality Factor, Q
$<1 \times 10^{-2}$	2
1×10^{-2}	2.5
1×10^{-1}	7.5
5×10^{-1}	11
1	11
2.5	9
5	8
7	7
10	6.5
14	7.5
20	8
40	7
60	5.5
1×10^{2}	4
$\geq 2 \times 10^{2}$	3.5

(a) Adapted from DOE 1981.

4.5 RECORDS

The primary purpose of the radiation records system is to document the external exposure of an individual. The employer should establish and maintain a consolidated record for each individual. Radiation records specifically related to the external exposure of an individual should be accumulated and retained in a single record file. A common feature of radiation protection programs is the use of individually assigned dosimeters to measure external radiation exposure incurred during some prescribed time interval. The presence of ionizing radiation and a measurement of it are shown by some physical or chemical change in the dosimeter, such as tracks in NTA film or CR-39, a discharge of an electrostatic chamber, or a change in an electrical

or magnetic property of a semiconductor. In each case, a record should be made of the quantitative change and the interpretation of this change in units corresponding to the permissible exposure limits.

Specifically, records should be kept of neutron and gamma exposure data and should be evaluated to determine whether exposures are being maintained as low as reasonably achievable (ALARA). Procedures should be established and supervision should assure that workers follow them in order to maintain their exposures ALARA. Total man-rem should be estimated for large tasks and a total man-rem dose established before initiating the job. Approximate radiation levels should be posted in work areas.

The current year's whole body internal-dose commitment from radionuclides for which the whole body is the critical organ must be combined with the external whole body dose (including neutron). Where both the external penetrating dose and internal dose to critical organ are known, they shall be combined for that organ. Where possible, critical organ dose will be determined by combining both external and internal contributions.

Records that may relate to neutron exposure that need to be maintained are listed in Table 4.3. This summary gives the retention period required by DOE Order 1324.2--Records Disposition, Chapter V - Retention of Contractor Records.

TABLE 4.3. Neutron Dosimeter Records

Record	Retention Period
Individual Radiation Dose Records	75 years
Radiation Detection Instrument and Dosimeter Calibration Records	75 years
Radioactive Sources Inventory and Records	Permanent
Onsite Radiation Monitoring Records	Permanent

5.0 TEST, MAINTENANCE, AND CALIBRATION

5.1 DEPARTMENT OF ENERGY LABORATORY ACCREDITATION PROGRAM

A national approach to the quality assurance and accreditation of radiological calibrations of personnel dosimetry services is being developed through the DOE Laboratory Accreditation Program (DOELAP). The DOE "Standard for the Performance Test of Personnel Dosimetry Systems" defines a set of reference performance tests to help establish a uniform approach to personnel dosimetry. The purpose of the standard is to describe minimum levels of acceptable performance and to provide procedures for the performance testing of personnel dosimetry systems.

Comparisons of occupational exposures reported for various DOE sites are complicated by the absence of standard calibration techniques and the use of many dosimeter designs. The establishment of reference calibration techniques will help quantify the effects of differing dosimeter designs and differing occupational environments. The choice of reference calibration sources given in this standard was based on an intercomparison of dosimeter system performances of DOE laboratories (Roberson et al. 1983) and the ANSI's Personnel Dosimetry Performance-Criteria for Testing N13.11 (ANSI 1983).

The standard applies only to personnel dosimetry systems used for determining whole-body dose equivalent for the permanent record. The standard is applicable for dosimetry performed for health protection under controlled and uncontrolled conditions (accident dosimetry). Tests for accident dosimetry are approximately represented by the high dose categories. The performance testing includes categories for the determination of dose equivalent (or absorbed dose) due to ionizing radiation only.

The standard also applies for specific energy intervals. The approximate intervals are from 15 keV to 2 MeV for photons, above 0.3 MeV for beta particles, and from 1 keV to 2 MeV for neutrons.

5.2 DOSIMETER MAINTENANCE

Care should be exercised to ensure that dosimeters are not placed in locations where they may be subjected to unusually high temperatures. They should

be kept free of dirt, oils, detergents, cologne, or other oily substances. Assigned personnel dosimeters shall not be worn during medical examination or treatment involving radiation exposures. Erroneous measurements may be obtained if personnel dosimeters become contaminated; therefore, every reasonable effort shall be made to avoid contamination. In radiation zones where two layers of protective clothing are required, the dosimeters should be worn on the inner layer. If worn on the outer layer, the dosimeters should be enclosed in a plastic bag or the equivalent to prevent contamination.

5.3 DOSIMETER CALIBRATION

Neutron calibration is defined as the determination of the relationship between the reading of a neutron dosimeter and the dose equivalent produced in tissue under the same exposure conditions. There are two types of calibration measurements which can be made. The first, a reference calibration, is a measurement of the response of a dosimeter to the neutron dose equivalent from a primary or unscattered field. The second, a field calibration, is a measurement of the response of the dosimeter under the conditions in which the dosimeter will actually be used. Calibration of personnel neutron dosimeters should be based on a technique traceable to the National Bureau of Standards (NBS) and on the response of the dosimeter to the field environment(s) according to the manner in which it is used. Calibration or correction factors should be determined which relate the response of the dosimeter in the field environment(s) to the response of the NBS traceable exposure.

The following sections will cover routine calibration of neutron dosimeters and remmeters with radioactive neutron sources. Generally, the material will refer to dosimeter calibrations, but most of the methodologies apply equally well to active survey instruments, such as remmeters or Bonner spheres. In principle, it is a very simple procedure: the dosimeter is placed at a convenient distance from a neutron source of known emission rate, and irradiated for a known time. The neutron fluence at the dosimeter is calculated from the emission rate of the source and its spectral information, its distance, and the time exposed. Using a conventional fluence-to-dose equivalent conversion factor, the dose equivalent to which the dosimeter has been exposed can be calculated. The dosimeter is then processed, and the reading corrected for

air and room scattering. The calculated dose equivalent, divided by the corrected reading, is the dosimeter calibration factor for that source. There are a number of uncertainties and detector deficiencies that contribute potential sources of error in the assessment of the dose equivalent from neutron dosimeter data. It is important to be aware of these sources so that they can be avoided, or, when unavoidable, controlled as much as possible. Such factors as source selection, choice of phantom, source-to-detector distance, and corrections applied for the scattering and attenuation of the neutrons all affect the accuracy of calibration.

Although there are several ways to perform adequate dosimeter calibrations, it is more important that everyone use the same procedure. Dosimeter calibrations should be a function only of the dosimeter type and the source's energy spectrum; they should not depend upon such factors as the source-detector distance or the room size. This is the only way in which the results of dosimeters from different laboratories can be compared, and the only way in which new dosimeter types can be evaluated.

5.3.1 Selection of Calibration Sources

Ideally, the neutron sources used for dosimeter calibration should approximate the spectra found at field exposure sites. This can be done by either closely simulating the fields in the laboratory or by performing field measurements or both. However, in practice the effects of shield moderation and room scatter, as well as spectra variation due to relocation of sources, may make effective simulation difficult. The calibration procedures used for the radiation fields shall be referenced to source fields standardized by NBS and be consistent with accepted national standards and practices. Reference class instruments, as defined in Requirements for an Effective National Radiation Measurement Program, Special Publication 603 (NBS 1981b), or related radioactive sources shall be used. The shape of the source should be spherical or cylindrical, and, in the latter case, it is preferable that the diameter and length are approximately the same. The thickness of the encapsulation should be uniform and small compared to the external diameter.

Most standards typically propose four neutron sources for calibration purposes: D_2O-moderated ^{252}Cf, ^{252}Cf, ^{241}Am-B, and ^{241}Am-Be. Other sources

which have been used for calibrations include PuBe, Pu-Li, PuF_4, and Am-Li. In addition, unidirectional beams of neutrons may be used. If the diameter of the beam is small compared to the dimensions of the measuring device under investigation, broad-beam irradiation may be simulated by appropriate sweeping of the measuring device across the beam. These sources may include thermal neutron beams, filtered neutron beams from reactors, and monoenergetic accelerator-produced neutrons. The neutron spectrum from D_2O-moderated californium sources has been accurately measured and found to be adequate for the calibration of albedo neutron dosimeters used at nuclear power plants. However, moderated californium sources do not adequately represent the spectrum associated with all neutron sources for the calibration of all dosimeters. Therefore, moderated and unmoderated californium sources were chosen for calibration reference sources for the National Voluntary Laboratory Accreditation Program (NVLAP) and DOELAP. Calibration improvement is an area of continuing research.

A ^{252}Cf neutron source has the following advantages as compared with the other sources: the neutron spectrum, which is similar to that from ^{235}U and plutonium fission, has been carefully evaluated and is well known; sources are available in any reasonable strength, are physically small (approaching a point source), and are relatively lightly encapsulated; the neutron emissions are close to isotropic; and the gamma contamination is lower than for any of the other sources. Because californium must be encapsulated, there is a finite amount of scattering, both elastic and inelastic, from the encapsulation. In the usual case of cylindrical encapsulation, the ratio of in-to-out scattering will vary as a function of orientation to the axis of symmetry of the source. Thus, the emission will no longer be isotropic. The modified ^{252}Cf source is moderated by 15 cm of D_2O and covered with 0.05 cm of cadmium. The dose equivalent response ratio of DOE albedo neutron dosimeters for moderated and unmoderated ^{252}Cf irradiations varies from approximately 6 to 20.

The principal disadvantage of ^{252}Cf is its relatively short half-life (2.6 years), which requires that it be replaced periodically. While this can be a problem in some laboratories, it should not be a serious handicap to most DOE laboratories.

The ^{252}Cf sources shall be calibrated in terms of neutron emission rate by NBS or another qualified laboratory using equipment and techniques referenced to NBS-maintained standards. Procedures for calculating the dose equivalent for exposed dosimeters shall follow Procedures for Calibrating Neutron Personnel Dosimeters, NBS Special Publication 633 (NBS 1982).

5.3.2 Phantoms/Irradiation Geometries and Facilities

During calibration it is important to simulate the conditions of dosimeter use (both in scattering and absorption) with a hydrogenous phantom representing the human body. As a rule of thumb, when the presence of a phantom alters the free-air response of the dosimeter by greater than 20%, a phantom shall be used during the calibration of the dosimeter. The human torso is a large neutron moderator and scatterer which significantly alters the neutron spectrum interacting with the dosimeter. The contribution of body scatter to the response of the dosimeter depends not only on the neutron spectrum but also on the dosimeter type; in particular, albedo dosimeters depend on body scatter for their response to fast neutrons. Albedo dosimeters obviously must be mounted on a phantom, and it is recommended that all dosimeters be irradiated on a phantom for calibration. The phantom shall be a polymethyl methacrylate ($CH_2=C(CH_3)\ COOCH_3$) slab, measuring 40 cm by 40 cm by 15 cm for neutron calibrations.[(a)] Although the minimum phantom dimensions necessary for body simulations depend on the neutron spectrum as well as the dosimeter response, the effective tissue thickness available for scattering is highly variable. It ranges from about 8 g/cm^2 over the lungs to nearly 20 g/cm^2 over the abdomen and the other, more solid, areas of the torso.

The dosimeters should be attached to the surface of the phantom facing the source (front face). For collimated beams, the central beam axis should be positioned perpendicular to and passing through the center of the front face of the phantom. For uncollimated beams, the center of the front face of the phantom is placed perpendicular to a radial line from the source center.

(a) Other plastics may be more appropriate for future systems.

Mount the dosimeters with the sensitive elements within the central 20-cm-by-20-cm area for neutron irradiations. The point of calibration should coincide with the center of the front face of the phantom.

To obtain an adequate calibration, choosing an appropriate source-to-detector distance (dosimeter plus phantom) requires some compromise. Too great a distance can lead to large room-scatter corrections. Too small a distance leads to nonuniform irradiation of the phantom, spectral variation, and uncertainty in the effective depth, introducing a relatively large uncertainty in the calibration factor. The source-detector distance is to be taken as the distance from the center of the source to the front face of the phantom directly behind the dosimeter. If several dosimeters are to be irradiated at the same time on the same phantom, the sensitive elements should be on the periphery of a circle centered on the face of the phantom, so that the dosimeters are all equidistant from the source. (The face of the phantom should be perpendicular to the line joining the source and phantom centers.) If this is not possible, explicit corrections should be made for the variation of the distance from the source for each dosimeter. However, when several dosimeters are irradiated simultaneously, precautions should be taken to keep the mutual interference much smaller than the uncertainty in the assigned dose equivalent.

An appropriate source-detector distance must be chosen for each source and facility configuration. However, if it has not been determined, it should be $\geq$50 cm for moderated ^{252}Cf.

Reducing the calibrations to "free-field" conditions is the only way in which calibrations can be made comparable between laboratories or new devices can be accurately compared to existing ones. This means that the fluence, or dose equivalent, delivered to the device is calculated assuming a "free field." The various scattering contributions are then treated as backgrounds which are subtracted from the reading of the device being tested. There are three sources of scattering background, each of which usually tends to increase the reading. Two of these, air scatter and source scatter, are often negligibly small, but the third, room return, is often very large. Laboratories can readily make corrections for these factors by using Monte Carlo

calculations. In general, irradiation rooms have thick walls for shielding, often made of concrete. In this case, the inside dimensions of the irradiation rooms should be as large as practical. The magnitude of the correction for room and air-scattered neutrons and the resulting uncertainty in the irradiation field quantities depend critically on the size of the room. In all cases, the effects of scattered neutrons need to be determined. The NBS Special Publication 633 (NBS 1982) gives some of the factors for scattering.

In practice, air scattering generally amounts to only a few percent of the neutrons arriving at the dosimeter, and the source asymmetry is usually small. However, since the albedo portion of the fast neutrons scattered from concrete and other building materials may be large, the contribution of room-reflected neutrons to the response of the dosimeter may be significant, particularly if the dosimeter is sensitive to the low-energy neutrons resulting from room scatter. These scattered neutrons have a different spectrum and a different variation with distance from the source. Therefore, they must not be considered a part of the calibration field, but should be considered a type of background, and appropriate corrections made.

For calibrations in a closed room, the source should be placed at, or near, the center of the room. The phantom should be placed on a low mass stand for minimum scattering, and should be the same height off the floor as the source. For outdoor calibrations, the source should be placed as high off the ground as practical.

5.3.3 Lower Limit of Detectability

The procedures for determining the lower limit of detectability should involve at least 10 dosimeters. The dosimeters should be placed in an unshielded environment for a time sufficient to obtain an unirradiated background signal typical of routine-processed dosimeters. For each expected neutron spectrum, a set of at least 10 dosimeters should be irradiated to a dose significantly (e.g., 10 times) greater than the estimated lower limit of detectability. Both the irradiated and unirradiated dosimeters shall be processed and evaluated. The lower limit of detectability should then be

determined as specified in the Standard for the Performance Testing of Personnel Dosimetry Systems (DOE 1986b).

5.3.4 Environmental Parameters/Fading

If dosimeters will be used outside the manufacturer's recommended temperature range or at temperatures which differ by more than 30°C from the calibration temperature, they shall be calibrated over the temperature range at which they will be used. Care should be taken to ensure that dosimeters are not exposed to temperatures that will damage detector or electronic components. Calibrations should be performed within the temperature range 25° ± 10°C.

If the manufacturer has not stated operating limits for humidity or atmospheric pressures, the dosimeters shall be calibrated at the approximate humidity or pressure expected to be encountered in use. Care should be taken to ensure that a dosimeter is not damaged by exceeding its pressure or humidity limits. The dosimeter response shall be corrected for fading such that the estimated dose equivalent is not in error, due to fading, more than ±40%.

Section 5.5 contains more information on how environmental parameters and fading affect the response of different dosimeter types.

5.3.5 Calibration Frequency

As a rule, before a new batch of dosimeters is placed in operation, relative dosimeter response is determined as a check on batch uniformity. If the batch uniformity test is carried out with a known exposure, it establishes the initial dosimeter calibration. Similar calibrations may be carried out prior to or immediately after each field use, preferably with the individual dosimeters permanently identified. Individual calibrations of this type are an advantage with highly reproducible systems and reproducible handling and readout techniques. Where system and technique variations during calibration of a large number of dosimeters are likely to introduce errors larger than those resulting from variations in response among individual dosimeters, less elaborate calibration methods are preferable. In addition to batch uniformity, the factors of dosimeter reproducibility, energy dependence, directional dependence, and environmental parameter response also need to be determined.

The calibration of personnel neutron dosimeters may be performed by the DOE site personnel with records describing the dosimeter calibration maintained onsite. The calibration should be repeated any time site personnel have reason to believe the neutron spectrum has changed and the previous calibration might not be valid. Calibrations of dosimeter response may also be performed by an offsite dosimeter processor. The processor should use a calibration factor applicable to the dose spectrum delivered to the individuals wearing the dosimeters.

5.3.6 Spectrometry

Dosimeters can be calibrated by exposing them to a known dose equivalent from a reference or calibration neutron source; however, the accuracy of this method depends upon how well the calibration spectrum matches the actual neutron spectrum in the work place. In the case of existing TLD-albedo dosimeters, few calibration sources actually match the spectra found in the work place. The neutron spectra used for calibration should simulate the work place spectra as closely as possible. The simulated spectra should include not only the direct source spectrum, but also the effect of moderation provided by shielding, scattering from walls and other structural materials, and spectral variations with location in the facility. This is especially important for calibration of TLD-albedo dosimeters.

Alternate methods of insuring the accuracy of personnel dosimetry include: 1) measuring the neutron flux density in the work place as a function of neutron energy and calculating the dosimeter response (assuming the dosimeter response is known as a function of neutron energy) or 2) exposing the dosimeter to a known dose equivalent in the work place, using spectrometric methods to determine dose equivalent. Spectrometric methods can be used to increase the accuracy of existing personnel dosimeters and instruments. In addition, spectral information can be used to calculate quality factors and dose conversion factors to account for future changes adopted by DOE or regulatory agencies. Effective dose equivalents can be calculated from neutron energy spectra and irradiation geometry data.

There are many different methods available for neutron spectroscopy, including multisphere or Bonner sphere techniques, proton recoil proportional

detectors, ^{3}He detectors, organic scintillators, photographic emulsions, ^{6}Li sandwich detectors, and activation foil techniques. Each of these techniques has problems inherent in its use. There is no ideal spectrometer that is highly accurate over the entire range of energies (thermal to over 1 GeV) found in DOE facilities. However, the majority of workers in DOE facilities are exposed to neutrons with energies below 20 MeV corresponding to moderated fission spectra (Brackenbush et al. 1980). Selection of the proper spectrometer system depends not only upon its energy range, but also such considerations as sensitivity, resolution, complexity of data analysis, portability, and the practical energy limits of the dosimetry system.

Neutron dose equivalent rates and quality factors are usually calculated from neutron flux measured as a function of incident neutron energy. However, quality factors and dose equivalent rates can be determined from measurements of linear energy transfer (LET) or lineal energy. Instruments such as TEPCs or recombination chambers can be used to determine lineal energy or LET distributions. The TEPCs directly measure absorbed dose in a small tissue-like site. Pulse height spectra from the TEPCs yield lineal energy spectra and information related to the LET of the secondary particles produced by the neutron radiation. With appropriate mathematical algorithms, average quality factors can be obtained by analysis of the data from TEPC measurements. This analysis can be performed by computer or by electronic circuitry.

With the exception of Bonner spheres, there is no commercially available neutron spectrometer that can be used to accurately determine neutron energy spectra in the work place. The DOE sponsored the development of a portable neutron spectrometer at PNL. Plans, specifications, schematic diagrams, and operating instruments for this spectrometer are available through PNL or the DOE Office of Nuclear Safety.

The PNL field spectrometer is based upon existing spectrometers. It is designed to cover the ranges of neutron energies involved in the processing of plutonium; it is not intended to be used at the higher energies associated with accelerator operations. The PNL field spectrometer uses a modular approach so that any portion that malfunctions can be easily replaced. The

system contains several modules: detector modules with their related electronics, a multichannel analyzer, and a computer to analyze and store the data. A portable field spectrometer unit, small enough to fit into a suitcase, was developed using commercially available components.

Two different types of detectors are used in the PNL prototype: ^{3}He proportional counters and TEPCs. The ^{3}He spectrometer measures neutron fluence as a function of incident neutron energy over an energy range of 50 keV to 5 MeV. The energy range can be extended using additional measurements. A TEPC measures the absorbed neutron dose and determines quality factors from lineal energy and LET distributions. The high voltage power supplies, the preamplifiers, and the amplifiers are built into the detector modules, so that a malfunctioning detector can be replaced as a unit without the necessity of recalibrating the unit. This involves the fabrication of special circuitry and printed circuit boards. Alternatively, commercially available NIMbin electronics can be used, but the unit would be larger and more expensive.

Although the prototype spectrometer used only TEPC and ^{3}He proportional counter detectors, other types of detectors can be used. The NE-213 liquid scintillator and pulse shape electronics being developed at LLNL, as well as the multisphere spectrometer, may be added in the future.

The analysis module uses a compact lap top computer to control the data collection and automatically analyze and record the data. The GRiDcase® computer selected for the prototype is fully IBM/PC compatible, so that the software developed for it can be used in IBM/PC clones presently used at many DOE facilities. Although a number of different multichannel analyzers are commercially available, an Ortec ADCAM unit was selected for ease of operation. This unit uses a separate Z80 microprocessor that runs independently of the GRiDcase computer, so that data collection and analysis can be performed simultaneously. The prototype has four inputs, so that four independent spectral measurements can be made at the same time.

The computer starts data collection at the push of a single button. After data has been collected for 30 minutes, the computer transfers the data into its memory, automatically analyzes it, and displays a summary of the

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results. This process is repeated until the operator pushes another button, or until a desired degree of statisical accuracy is achieved. The computer then analyzes the data and places the analyzed results and raw data on a hard disk for permanent storage. The process is so automated that the spectrometer can be used in the field by individuals who have limited training in neutron spectrometry. A summary of the specifications for the PNL prototype field spectrometer is given in Table 5.1. Additional information on fabrication of the spectrometer and its performance characteristics are given in a PNL report scheduled for release in early 1988.

TABLE 5.1. Specifications for the Field Spectrometer

Size of Analysis Module	9 in. x 18 in. x 24. in.
Weight of Analysis Module	40 pounds
Power Requirements	110-120 VAC, 50-60 Hz
Detectors	^{3}He proportional counter and TEPC (multisphere and NE-213 spectrometers may be added)
Operating Energy Range	50 keV to 5 MeV for ^{3}He and thermal to 20 MeV for TEPC
Dose Rate Range	0.1 to 100 mrem/h, depending on the size of detectors
Gamma Interference	Rejection of 500:1 photon to neutron, depending on size

5.3.7 Quality Control

Quality control (QC) is an element of the total quality assurance (QA) program that is often and erroneously considered to be synonymous with QA. The QC element is basically concerned with the testing and verification of performance and materials. Thus, testing and evaluation of a personnel dosimetry system to verify that in fact performance specifications have been met is a QC function, and is but a part of the total QA program involving that system. The whole QA program includes such considerations as establishing procedures for monitoring, calibrating, documentating calibrations, repairing equipment, acceptance testing, etc. The list of QA activities can be very long.

A good radiation-protection program uses the proper dosimetry systems. Often, suitable systems can be purchased by ordering directly from one of the several vendors of radiation-protection equipment. The catalog specifications are assumed to be those that the manufacturer claims for the model number or series under negotiation. The procurer must assure that every required capability is specified. One item mistakenly omitted may lead to receiving a device unsuitable for service in the user's particular application. Some performance specifications are worthy of note in a suitable neutron dosimetry system:

- accuracy
- energy range
- energy dependence
- dose equivalent range
- dose equivalent rate range
- lower detection limit
- angular response
- gamma interference
- stability
- readout reproducibility and methodology
- ultraviolet sensitivity
- temperature range
- humidity stability
- cost
- weight
- size.

When the dosimeters are received, all devices should be tested against the critical specifications to the extent practicable. Even in small radiation-protection groups, the need for acceptable radiation measurement systems warrants thorough acceptance testing. The services of an independent testing laboratory may be required for performance of some of the tests. Some facilities may desire to test a sampling of the devices against all of the specifications. In this case, dosimeters should be selected randomly from the lot in order to obtain a representative sample of operating characteristics.

Adequate documentation of the results of the tests is needed so that malfunctioning units can be discarded or repaired. A system should be devised to assure that defective units are not placed into service inadvertently.

A dosimeter should always be given some degree of evaluation before being used. When new types of devices are procured, it is important for management to assure that proper training be given to the staff concerning the use, limitations, and care of the dosimetry systems.

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APPENDIX A

PERFORMANCE CHARACTERISTICS

APPENDIX A

PERFORMANCE CHARACTERISTICS

IDEAL DOSIMETER

Many types of neutron detectors may be useful as personnel neutron dosimeters. The following criteria have been developed for an "ideal" personnel neutron dosimeter:

- sensitivity, or lower detection limit - The dosimeter should be able to measure down to at least 10 mrem for almost any neutron energy.
- interference from other radiations - The dosimeter should be insensitive to photons and beta particles.
- stability - The dosimeter should not fade with time.
- environmental factors - The dosimeter should not be affected by sunlight ambient temperature, humidity, pressure, or mechanical shock.
- energy response - The dosimeter's response should follow the dose equivalent as a function of neutron energy. If this is not possible, the dosimeter should indicate neutron fluence and energy, or neutron absorbed dose (in rad) and quality factors.
- cost - The dosimeter materials should be inexpensive to allow widespread use. The processing and readout of the dosimeter should be simplified or automated to minimize readout errors and reduce readout costs.
- other factors - Personnel dosimeters should be easily worn by the user. They should not present toxicity hazards.

COMBINATION TLD/TED

The dosimetry-grade CR-39 track etch dosimeter (TED) is being used with TLD-600s and -700s as a combination dosimeter that responds over a wide range of energies. Fast neutrons above about 100 keV can be detected by interactions in CR-39 either directly or by recoil particles from a radiator. Lower energy neutrons reflected from the body (albedo) are detected by the TLD component. By using a combination of direct interactions plus the albedo technique, the dosimeter can nearly match the fluence-to-dose equivalent conversion curve. The combination dosimeter yields a nearly correct dose equivalent regardless of the energy of the incident neutrons. Design parameters for the combination TLD/TED are summarized in Table A.1.

TOTAL DOSE METER

Another new type of radiation detection system that has been developed uses a tissue equivalent proportional counter (TEPC) as the detector. The TEPC consists of a proportional counter filled with tissue equivalent gas and constructed with walls of tissue equivalent plastic. Radiation interacts with the tissue equivalent plastic walls to form charged particle secondaries, which deposit energy through ionization in the cavity of the proportional counter. The pulse from the proportional counter is directly proportional to the energy deposited. Thus, by simply summing the energy deposited by radiation induced events and dividing by the mass of gas in the counter, a direct measure of absorbed dose in a tissue equivalent material can be obtained. Design parameters for the total dose meter are summarized in Table A.2.

TABLE A.1. Combination TLD/TED Design Goals

Criteria	1987 Status	Near-Term Goal (2 to 3 Years)	Long-Term Goal (7 to 10 Years)
TLD/TED			
Accuracy	TED at 10 mrem ±25% TLD at 50 mrem ±100%	TED at 10 mrem ±20% TLD at 50 mrem ±100%	TED at 10 mrem ±10% TLD at 50 mrem ±50%
Energy Range	TED - 100 keV to 18 MeV TLD - Thermal	TED - <25 keV to >18 MeV TLD - Thermal	TED - Thermal to >18 MeV
TED			
Energy Dependence	±100%	±50%	±15%
Dose Equivalent Range	10 mrem to >400 rem	1 mrem to 1000 rem	0.1 mrem to 10,000 rem
Dose Equivalent Rate Range	N/A	N/A	N/A
Lower Detection Limit	10 mrem ±25%	1 mrem ±50%	0.1 mrem ±50%
Angular Response	±80% (2π)	±50% (2π)	±20% (2π)
Gamma Interference	N/A	N/A	N/A
Stability	Background increase by a factor of 2 to 3 over 1 year	Background increase by a factor of 100% over 1 year	Background increase by a factor of 100% over 1 year
Readout Reproducibility	±20%	±10%	±5%
Ultraviolet Sensitivity	Sensitive to direct UV	UV blocking cover	UV blocking cover
Temperature Range (°F)	0 to 120°	-30 to 150°	-30 to 150°
Humidity Stability	0 to 100%	0 to 100%	0 to 100%
Processing	Electrochemical processing with conventional optical readout	Rapid chemical processing with fourier transform readout analysis	Self-developing dosimeter with fourier transform readout analysis
Unit Cost (Foil)	TED - $0.30-$0.60 Badge - $25.00	TED - $0.30 Badge - $15.00	TED - $0.30 Badge - $5.00

TABLE A.2. Total Dose Meter Design Goals

Criteria	1987 Status	Near-Term Goal (2 to 3 Years)
Accuracy	At 10 mrem ±50% gamma and neutron	At 10 mrem ±20% gamma and neutron
Energy Range	Fission energies (neutron) and 150 keV to 1.3 MeV (gamma)	Fission energies (neutron) and 150 keV to 1.3 MeV (gamma)
Energy Dependence	±30%	±20%
Dose Equivalent Range	1 mrem to 1 rem	1 mrem to 10 rem
Dose Equivalent Rate Range	0.01 to 1 rem/h	0.01 to 5 rem/h
Lower Detection Limit	1 mrem ±50%	1 mrem ±50%
Angular Response	±15% (2π)	±15% (2π)
Gamma Interference	N/A	N/A
Stability	±15% over 3 years	±15% over 3 years
Temperature Range	40° to 95°F	40° to 130°F
Humidity Range	0% to 90%	0% to 90%
Weight	1.5 lbs	1 lb
Unit Cost	$3000	<$1000

APPENDIX B

OTHER NEUTRON DOSIMETERS

APPENDIX B

OTHER NEUTRON DOSIMETERS

B.1 PASSIVE SYSTEMS

In addition to the dosimetry systems described in Section 4, there are systems that are not widely used for personnel neutron dosimetry by DOE or DOE contractors that will be briefly described here. In addition, a list of the potential future passive and active systems is provided.

B.1.1 Fission Fragment Recoil Track Etch Dosimeters

Fission track neutron dosimeters are in limited use for specific applications such as area monitoring. The dosimeter consists of a fissionable radiator and an adjacent track detector material (usually polycarbonate) to detect the fragments. Neutrons interact with the radiator to produce fission fragments, which are easily recorded by the track detector. Using fissionable materials as particle radiators provides a well-defined energy response since the differential fission cross sections of commonly used elements are well known. After irradiation, the plastic can be etched in a chemical solution to enlarge the fission tracks, which are then counted.

The four popular radiators used in fission track dosimeters are ^{235}U, ^{238}U, ^{232}Th, and $^{237}NpO_2$. Thorium has a fission threshold of about 1 MeV for neutrons and a differential fission cross section which increases rapidly with energy above this threshold. Thus, thorium-based dosimeters are best used in environments with high energy neutrons. Neptunium has a fission threshold in the thermal energy range and a differential cross section which is within about 30% of the ICRP dose equivalent for neutron energies from thermal to approximately 1 MeV. These dosimeters are sensitive to neutrons over a wide range and have a nearly tissue-equivalent response.

These dosimeter types have the advantages of having well-defined energy response characteristics, being insensitive to interfering gamma and beta radiations, and exhibiting little or no fading at temperatures below about 50°C. The primary disadvantages of fission track dosimeters are that 1) the

fission radiator emits gamma rays that provide radiation doses to the wearer, 2) the material is chemically toxic, and 3) there may be administrative restrictions concerning the possession, movement, and accountability of the fissionable materials.

B.1.2 Superheated Liquid Drop (SLD) Dosimeters

The superheated drop detector, a miniature bubble chamber, is a simple device for the detection of neutrons and charged particles. A liquid fluorocarbon is injected into a viscous gel under pressure, or an emulsion of very small droplets is created in a gel or polymer. A charged particle or neutron recoil can trigger nucleation in the superheated liquid and instantly convert it to a gas. Photons cannot impart enough energy to cause vapor formation, so the device is completely insensitive to gamma and x-rays. If enough energy is imparted in a small volume, a microscopic bubble is formed. If the diameter of the bubble is large enough, the bubble becomes thermodynamically unstable and grows; if not, surface tension collapses the bubble. The bubbles can be counted optically (or acoustically by an active dosimeter) and be related directly to dose.

There are significant advantages to the superheated drop detector:

1) It is insensitive to gamma rays.
2) The sensitivity can be increased by increasing the amount of superheated liquid.
3) A crude neutron energy spectrometer can be constructed by using mixtures of liquids with various degrees of superheat, hence, various energy thresholds.
4) The dosimeter can be made to be readable by the wearer and can be made active or passive.

The major disadvantage of SLD dosimeters, however, is that they are relatively new. Research and development (R&D) has not progressed to the point where they can be considered for adoption. A discussion of R&D requirements for this dosimeter is not within the scope of this document.

B.2 ACTIVE SYSTEMS

Three active neutron dosimetry systems will be briefly described in this section: the pocket rem meter, the total dose meter, and semiconductor dosimeters.

B.2.1 Pocket Rem Meter

The pocket rem meter is an electronic detector package weighing 630 grams (1 lb., 6 oz), having dimensions of 20.3 cm (8 in.) by 7.6 cm (3 in.) by 5.1 cm (2 in.). It fits into "large-sized" pockets and is similar in size to a walkie-talkie. It contains three cylindrical tissue-equivalent proportional counters (TEPCs) to obtain the desired sensitivity of the instrument. Each of these neutron detectors is 1.9 cm (3/4 in.) in diameter by 13 cm (5-1/4 in.) in length. The pocket rem meter runs 40 hours on a single 9-volt battery, displaying a low-voltage signal when the battery needs replacement.

Neutrons or other types of ionizing radiation interact with the tissue-equivalent plastic walls of the detectors to produce charged particles, which traverse the gas cavity. The gas pressure is so low that most particles have a constant energy loss in traversing the cavity. Electronic signals from the cylindrical TEPCs are processed using hybrid circuitry and are routed to a 256-channel analog-to-digital converter. Digitized signals are sent to a CMOS microprocessor, which calculates neutron dose equivalent, absorbed dose, counts from the TEPCs, and data acquisition time. Two liquid crystal displays are used to present the neutron dose equivalent, absorbed dose, TEPC counts, and time.

The TEPC gives an absolute measure of the absorbed dose in a tissue-equivalent medium. A built-in algorithm is used to calculate dose equivalent. All events producing pulses above 10 keV/μm are considered to be neutron pulses. The pulse height is adjusted to be numerically equivalent to linear energy transfer (LET). Since quality factors are currently defined in terms of LET, it is possible to determine quality factors directly from the distribution of pulse heights.

B.2.2 Total Dose Meter

The total dose meter is an instrument capable of measuring the absorbed dose from gamma rays, neutrons, and penetrating high-energy charged particles using a single TEPC. Although the TEPC detector tube has the same dimensions as the pocket rem meter, it has an improved design that simulates a tissue-site diameter of only 1 μm. A simple built-in empirical algorithm is used in a microprocessor to determine the dose equivalent from mixed radiations, with the results shown on a liquid crystal display on the top of the instrument. In addition to displaying the total millirem dose equivalent, the instrument provides an audible alarm if the accumulated dose equivalent exceeds 100 mrem. For ease of decontamination, the controls are actuated by waterproof pressure-sensitive switches on the side. The controls include an on/off switch, a switch to acknowledge and shut off the alarm, and a switch to turn on an electroluminescent panel to illuminate the display in the dark. It has an operating range of 1 mrem to 10 rem (limited by the number of digits in the display) and a minimum sensitivity of about 0.2 mrem for neutrons; however, it currently displays the nearest mrem.

The total dose meter is smaller (6 in. by 3 in. by 1-3/4 in.) than the pocket rem meter and measures the dose equivalent from both neutrons and photons. Both the pocket rem meter and total dose meter have the additional advantage that if neutron or photon quality factors are changed in the future, the microprocessor can be reprogrammed with a different algorithm to accurately determine the "new" dose equivalent.

B.2.3 Semiconductor Dosimeters

Semiconductor devices combined with proton radiators can be used as dosimeters to measure neutron dose. The systems can be designed as either passive dosimeters, active dosimeters, or spectrometers.

One "active" dosimeter approach is to use a silicon diode for neutron dosimetry. In this system, a N/P semiconductor device covered with a polyethylene film is exposed to a neutron flux. A fraction of the neutrons are converted to protons by (n,p) reactions in the radiator. A significant fraction of the protons escape the film and enter the semiconductor device. In

addition, neutrons which pass through the radiator into the silicon device may undergo a (n,p) reaction, thus producing protons throughout the silicon material. The protons from both reactions will create electron hole pairs in the silicon, which can then be measured electronically as a function of real time.

APPENDIX C

DOSIMETRY ERRORS

APPENDIX C

DOSIMETRY ERRORS

There are a number of uncertainties and detector deficiencies that contribute potential sources of error in the assessment of the dose equivalent from neutron dosimeter data. It is important to be aware of these sources so that they can be avoided or, when unavoidable, controlled as much as possible.

C.1 OPERATIONAL DIFFICULTIES

Calibration uncertainties, equipment malfunction, and personnel errors can be minimized by establishing detailed written procedures for the step-by-step techniques required to yield reproducible results.

C.2 DETECTOR DEFICIENCIES

Physical errors attributable to the detector can result from such things as gamma interference, incorrect spectral response or total lack of response in specific portions of the spectrum, poor reproducibility, and loss of information due to fading, temperature or other ambient stresses. Many of these limitations can be minimized by suitable controls, calibration, and procedures. However, such inadequacies as total insensitivity at certain energies or poor approximation to the dose equivalent are serious problems. In situations where there is significant spectra variation from one radiation area to another, it is important that individual consideration be given to each area. To cover areas of insensitivity, separate calibrations may be required for different areas or even different dosimeters.

C.3 GEOMETRIC UNCERTAINTIES

Geometric errors occur because of source size, source distribution, and variation in source-to-dosimeter distances. Orientation introduces large errors when a single dosimeter is attached at one position on the body, particularly if the body is stationary and the source is unidirectional; yet

it is impractical to cover the individual with dosimeters to measure orientation or vertical and horizontal distributions. Therefore, it may be important to augment dosimeter data with field surveys that use additional instrumentation to help reduce or eliminate many of these uncertainties.

C.4 CALIBRATION ERRORS

This is discussed in detail in Section 6.0 of this document.

C.5 IMPACT OF ENVIRONMENTAL PARAMETERS

This is discussed in detail in Section 5.5.

APPENDIX D

PROCESSING PROCEDURE FOR "HOT" ELECTROCHEMICAL ETCHING OF CR-39

APPENDIX D

PROCESSING PROCEDURE FOR "HOT" ELECTROCHEMICAL ETCHING OF CR-39 TEDS

The most important requirements in processing CR-39 TEDs are, first, that each system maintain consistency in processing to avoid parameter-induced changes in response and, second, that the system's dose response be calibrated for the expected spectra.

The "hot" electrochemical etch process has undergone considerable development and optimization. Procedures for its use are outlined in the following section and assume the use of a 8- or 24-cell chamber. These procedures may be modified as additional data suggest changes.

D.1 LOADING OF ELECTROCHEMICAL ETCH CHAMBERS

a. Check the oven temperature and adjust to 60°C, if necessary.

b. Enter information relating to the CR-39 dosimeter foils and etching parameters in the daily log book and on the counting form or the computer.

(1) Name of person performing processing

(2) Counting date

(3) Etch chamber identification

(4) KOH normality

(5) Image analysis reader settings

(6) Temperature of oven

(7) First etching-step parameter

- High voltage
- Frequency (Hz)
- Etching time

(8) Second etching-step (blow up) parameters (to increase size of already established tracks)

- High voltage
- Frequency (Hz)
- Blow up time

(9) CR-39 sheet number

(10) Identification number of each CR-39 foil

(11) Identification of exposure to foils (worn by, placed at, background, calibration dose, etc.)

c. Remove the protective polyethylene cover from the front and back of the foil using a scalpel or knife.

d. Position CR-39 foils face down on the O-ring around the cell opening. Place foils in order on the etch chamber, using the identification number on the foil.

e. Connect the chamber to the vacuum system using the chamber's vent hole. Accurately position the foils over the opening and turn on the vacuum. It may be necessary to press the foils down onto the O-rings using the thermoplastic pressure plate before a good seal can be obtained. The vacuum will hold the foils securely while the etch chamber is being assembled.

f. Place a 10-mil piece of polyethylene over the foils.

g. Place the aluminum plate on top of the polyethylene. This aluminum plate is the second electrode.

h. Place the Lucite pressure plate on top of the chamber and secure it to the chamber body with the bolts and wing nuts. The wing nuts should be securely fastened by using fingers only.

i. Shut off the vacuum and remove the hose. Plug the pressure gauge system into the vent hole to test the chamber for leaks. The pressure will remain constant if a good seal has been made and the chamber does not leak.

j. Place the chambers and the KOH bottle in the oven and leave there overnight. Remove the chambers and the KOH from the oven the next morning and immediately partially fill the chamber approximately 3/4 full with KOH through the vent hole. Secure a rubber, one-hole stopper in the vent hole. This prevents spillage when the cell is tipped but still allows air to vent through the small hole.

k. Attach the high-voltage leads to the electrodes (rod and aluminum plate) using the alligator clamps or telephone jacks.

l. Place the chamber in a plastic tray in the oven with the vent hole positioned at the front of the oven. The oven racks must slant slightly to the rear of the oven. This prevents the KOH from being forced out through the small hole in the stopper if the KOH and air expand.

m. Check the power supply parameters for the automated power supply. The recommended "hot" electrochemical etching parameters are:

	Etching	Blow Up	Post Etch
High Voltage	3000 V	3000 V	0
Frequency	60 Hz	2000 Hz	0
Temperature	60°C[(a)]	60°C	60°C
Time	5 hours	23 minutes[(b)]	about 15 minutes
KOH Normality	6.5 N	6.5 N	6.5 N

(a) The etch chambers and KOH must be left in the oven overnight (or weekend).
(b) No adjustment for foil thickness is required if the foils are 25 mil ± 3 mil.

n. Check the oven temperature and high voltage periodically during the etching cycles.

o. Leave the chambers in the oven for a 15-minute postetch period following the completion of the etch cycles. This is not required bugt tends to round the tracks somewhat. The postetch should not last more than 25 minutes.

D.2 UNLOADING OF ELECTROCHEMICAL ETCH CHAMBERS

Empty the chamber of KOH by removing the stopper and pouring the KOH back into the bottle. Use a funnel to prevent excessive spillage. The KOH solution may be reused several times. Rinse the chamber with tap water at least twice. Then take it apart, rinse all the parts, and leave them to air dry. Soak and rinse the foils in distilled water for about 5 minutes. Then remove the foils and blot them dry using paper towels. Before reading them, wipe them with lens paper.

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