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Personnel Neutron Dose Assessment Upgrade

Volume 2: Field Neutron Spectrometer for Health Physics Applications

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**Pacific Northwest Laboratory
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PERSONNEL NEUTRON DOSE ASSESSMENT UPGRADE

VOLUME 2: FIELD NEUTRON SPECTROMETER
FOR HEALTH PHYSICS APPLICATIONS

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FOREWORD

Both the International Council on Radiation Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP) have recommended changes in radiation protection standards. These changes include an increase in neutron quality factors and the adoption of effective dose equivalent methods. The series of reports entitled Personnel Neutron Dose Assessment Upgrade (PNL-6620) addresses these changes. Volume 1 in this series of reports (Personnel Neutron Dosimetry Assessment) provided guidance on the characteristics, use, and calibration of personnel neutron dosimeters in order to meet the new recommendations. It was also recognized by the Health Physics Branch of the Department of Energy (DOE) Office of Nuclear Safety that a capability to rapidly measure neutron energy spectra in the workplace would assist considerably in implementing these recommendations. A priority fast track development program was initiated in January 1987 to respond to this need. This report, Volume 2: Field Neutron Spectrometer for Health Physics Applications, represents the culmination of this effort and describes the development of a portable field spectrometer which can be set up for use in a few minutes by a single person. (Volume 3 in the series will provide the computer code used in analyzing data from the field neutron spectrometer.)

One of the major concerns in responding to the recommended change in neutron quality factor (Q) under the current system of measurement is the effect on assessment, reporting, and control of neutron exposures to workers. A large part of the conservatism in current neutron exposure assessment is attributed to the lack of neutron energy information associated with the radiation. While quality factor varies as a function of neutron energy, the lack of a measurement system to provide energy spectral information necessitates the application of the maximum Q in the interest of conservatism in estimating worker dose. As a result, applying a factor of 2 change to the neutron quality factor under the current system of measurement would result in simply doubling the current reportable neutron exposures.

The field spectrometer described herein represents a significant advance in improving the accuracy of neutron dose assessment. It permits an

immediate analysis of the energy spectral distribution associated with the radiation from which neutron quality factor can be determined. It is now possible to depart from the use of maximum Q by determining and realistically applying a lower Q based on spectral data. The field spectrometer is made up of two modules: a detector module with built-in electronics and an analysis module with a IBM PC®-compatible computer to control the data acquisition and analysis of data in the field. A modular approach is used in order that defective components can be easily replaced. The unit is simple enough to allow the operator to perform spectral measurements with minimal training. The instrument is not intended for use in accelerator-produced pulsed radiation fields, but rather for use in steady-state radiation fields with neutrons energies covering the fission spectrum range. The prototype field spectrometer has been field tested in plutonium processing facilities, and has been proven to operate satisfactorily.

The prototype field spectrometer uses a ^3He proportional counter to measure the neutron energy spectrum between 50 keV and 5 MeV and a tissue equivalent proportional counter (TEPC) to measure absorbed neutron dose. These detectors were selected because they are self-calibrating and do not require exposure to a calibrated neutron source. The unit is sensitive enough to display energy spectra, determine average quality factors and dose equivalent rates in a few hours when exposed to neutron fields from 1 to 10 mrem/h. Other detectors responding to higher energy neutron can be added later, if desired.

This report contains detailed plans and cost estimates for building the portable spectrometer, using either the PNL developed electronic circuitry or commercially available NIMbin electronics. Depending upon the number of detectors and the type of computer selected, current costs of components for the field spectrometer range from \$8000 to \$20,000. These costs are comparable to those for existing commercially available computer-based multichannel analyzers for gamma spectrometry. Complete descriptions are included for the construction of the necessary electronics, step-by-step operating instructions, and a trouble-shooting guide.

In the interest of improving neutron dose assessment of workers, DOE contractors should consider the procurement and use of the described field

spectrometer. Should any questions arise concerning design, construction, and use of the spectrometer, please communicate with Larry Brackenbush, Pacific Northwest Laboratory. He may be reached on (509) 375-6853.

A handwritten signature in black ink, appearing to read 'EJV', followed by a horizontal line.

E. J. Vallario
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EXECUTIVE SUMMARY

Various advisory organizations have proposed changes in radiation protection standards, including changes in quality factors and adoption of effective dose equivalent methods. Measurements of neutron energy spectra in the workplace will make it possible to calculate the effects of adopting any of these proposed changes. In addition, neutron spectral measurements and determination of dose equivalent rates will make it possible to improve the accuracy of existing neutron dosimetry.

This report describes the development at the Pacific Northwest Laboratory (PNL) of a portable field neutron spectrometer suitable for measurements in plutonium facilities. This spectrometer is not suitable or intended for measuring the much higher energies at high-energy accelerator facilities. Because suitable neutron-energy spectrometers are not commercially available, the U.S. Department of Energy (DOE) initiated the development of this spectrometer.

A single person can carry it into the workplace and assemble and operate it in a few minutes. Included in this report also are instructions for assembling and operating the spectrometer. The modular approach used in constructing the spectrometer allows defective components to be easily replaced in a few minutes.

The prototype field spectrometer is based on two modules: 1) a detector module with built-in electronics and 2) an analysis module with an IBM PC-compatible computer to control the data acquisition and analysis of data in the field. The unit is simple enough to allow an operator with a minimum of training to make spectral measurements.

One version of the field spectrometer uses a ^3He proportional counter to measure the neutron energy spectrum between 50 keV and 5 MeV and a tissue equivalent proportional counter (TEPC) to measure absorbed neutron dose and to estimate quality factors for neutrons with energies between thermal and 20 MeV. These detectors were selected because they are self-calibrating and do not require exposure to calibrated neutron sources. The spectrometer is sensitive enough to measure energy spectra and to determine average quality factors and dose equivalent rates in a few hours when exposed to neutron

fields from 1 to 10 mrem/h. Other detectors that can be used to cover higher energy ranges can be added to this unit later, if needed.

This report contains detailed plans and cost estimates for building portable spectrometers using either the PNL-developed electronic circuitry or commercially available nuclear instrument module bin (NIMbin) electronics. Depending on the number of detectors and the type of computer used, costs for the field spectrometer range from \$8000 to \$20,000. These costs are comparable to those for commercially available computer-based multichannel analyzers (MCA) for gamma spectrometry. Complete descriptions are included for constructing the necessary electronics, as are detailed listings and explanations of the computer analysis codes, step-by-step operating instructions, and a trouble-shooting guide.

The prototype field spectrometer has been field tested in plutonium processing facilities and has been demonstrated to operate satisfactorily. However, several improvements could be added. These include installing an alpha calibration source in the TEPC so that measurements can be made in neutron fields of only a few tenths of millirem per hour. Higher pressure ^3He proportional counters are also recommended to increase sensitivity to higher energy neutrons. Power line transients can cause loss of data, unless the data is recorded periodically. With these improvements, the field spectrometer could make reasonably accurate determinations of quality factors and dose equivalent in a facility in less than an hour.

Because of this size of the analysis computer code, a separate document containing and describing the code will be issued shortly. The code will be made available through a code distribution center such as the Radiation Shielding Information Center (RSIC). Details of the code will be included in the companion document.

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1.0 INTRODUCTION

1.1 NEED FOR SPECTROMETRY

Recent changes in radiation protection standards will require an increased knowledge of the neutron energy spectrum in the workplace. The U.S. Department of Energy (DOE), Office of Nuclear Safety (ONS), Health Physics Branch has sponsored the development of portable neutron energy spectrometers to improve measurements in the workplace. These efforts are part of a larger program established by DOE to improve the accuracy of neutron dosimetry. This report describes the development at the Pacific Northwest Laboratory (PNL)(a) of a portable field neutron spectrometer to perform spectral measurements.

Various national and international organizations have recently recommended changing neutron quality factors and the methods used to determine dose equivalent. In the National Council on Radiation Protection and Measurements (NCRP) Report 91, Recommendations on Limits for Exposure to Ionizing Radiation (NCRP 1987), the NCRP recommended increasing quality factors for neutrons specifying that where the neutron energy spectrum is not known, a value of 20 is recommended for fast neutrons. Also, in Radiation Protection Guidance for Federal Agencies for Occupational Exposure (Presidential Documents 1987), the President has accepted the Environmental Protection Agency (EPA) guidance that federal agencies adopt the methodology of the International Commission on Radiation Protection (ICRP) Publication 26 (ICRP 1977) for determining effective dose equivalent. ICRP Publication 51, Data for Use in Protection Against External Radiation (ICRP 1987), gives some guidance on how to determine effective dose equivalent for external radiations. The U.S. Department of Energy (DOE) is expected to adopt some of these recommendations in the near future.

Approximately 25,000 radiation workers at a number of DOE facilities are exposed to neutrons in the conduct of their work (Brackenbush and Endres 1980). Unfortunately, in most of these facilities, the neutron sources are

(a) PNL is operated by Battelle Memorial Institute for the U.S. Department of Energy under contract DE-AC06-76RLO 1830.

not well defined; i.e., the source strength and neutron energy spectra are not well known. To avoid unnecessary conservatism in neutron dosimetry, it is highly desirable to measure the neutron fields in the workplace. This information is beneficial for the following reasons:

- Increased accuracy can be achieved by field calibration of personnel dosimeters and instruments. Typically, neutron dosimeters are calibrated in the laboratory using a standard neutron source. However, the neutron energy spectrum and irradiation geometry in the workplace are usually different than those in the calibration laboratory. A correction factor is applied to account for these differences. Correction factors specific to actual work locations can be determined by exposing dosimeters on a phantom at locations where the dose equivalent has been determined from spectral measurements.
- Spectral information will allow calculating quality factors and dose equivalent conversion factors.
- Effective dose equivalent can be calculated from neutron energy spectra and irradiation geometry using the data in ICRP Publication 51 (1981). Because effective dose equivalent accounts for attenuation and degradation of energy of neutrons penetrating the body, adopting effective dose equivalent can mitigate the effects of increases in quality factor.

1.2 DESCRIPTION OF THE FIELD SPECTROMETER

With the possible exception of the Bonner sphere spectrometer, no commercially available neutron energy spectrometer used by operational health physicists can accurately determine neutron energy spectra in the workplace. The DOE is sponsoring the development of portable neutron spectrometers at PNL and Lawrence Livermore National Laboratory (LLNL). The PNL effort is based on using existing technology and is a short-term effort; the LLNL effort is based on developing custom electronic circuitry for a NE-213 scintillator spectrometer and is a long-term effort. This report describes the PNL spectrometer development efforts; the LLNL spectrometer development will be described in future reports.

Figure 1.1 shows the prototype field neutron spectrometer developed at PNL. The unit is completely portable and can be carried into the workplace and set up in only a few minutes. The spectrometer design is based on a modular approach, so that it can easily be repaired in the field by exchanging modules. Two different types of detector modules are used in the prototype: 1) a tissue equivalent proportional counter (TEPC) with built-in electronics and 2) a ^3He proportional counter with built-in electronics. The heart of the field spectrometer is the analysis module mounted in the suitcase shown in the middle. The analysis module is based on a lap-top computer that controls the data collection, analyzes the data in the field, and displays the results to the operator. After sufficient data is collected,

FIGURE 1.1. The Prototype Field Neutron Spectrometer Developed by PNL

the computer writes out the analyzed results and data from the detectors to a disk in the computer for permanent storage.

The computer displays several quantities for consideration by the operator. The differential neutron flux density as a function of neutron energy between 50 keV and 5 MeV is displayed graphically for the operator. The computer also calculates average neutron energy, average neutron quality factors, and the average dose equivalent rate, and displays a summary of this information for the operator. At present, the analysis program uses the current values for quality factors and flux-to-dose equivalent conversion factors listed in NCRP Report 38, Protection Against Neutron Radiation (NCRP 1971a). Once the neutron energy spectra and the absorbed dose distributions are measured, it is possible to calculate the results of future changes for quality factors or effective dose equivalent. The spectrometer is designed to measure the neutron fields in plutonium facilities. Future modifications will further extend its energy range.

1.3 CONTENTS OF REPORT

This document describes all aspects of the field spectrometer, including a description of the nuclear principles on which it is based, a description of the analysis algorithms, ways to construct several different variations of the spectrometer, detailed operating instructions, a trouble-shooting guide, and details of the computer program used to control the spectrometer and analyze the data. Because of the size of the computer program used to acquire and analyze the data, a separate document (Volume II) is being prepared to describe and list the computer program. A synopsis of this report is given below.

Section 2.0 provides the basis for selecting different types of detectors used (^3He proportional counters and TEPCs).

Section 3.0 describes the theory of the operation of ^3He proportional counters. This includes a theoretical treatment and derivation of the unfolding algorithms used to determine the neutron flux density.

Section 4.0 describes the theory of operation for the TEPC, including an explanation of how the TEPC functions and how it is used to determine

absorbed dose. It also includes an explanation of the algorithms used to derive quality factors and dose equivalent from the pulse height spectrum measured by the TEPC.

Section 5.0 describes the operation of the field spectrometer. It assumes the operator has no prior experience.

Section 6.0 describes the results of actual measurements in plutonium facilities and discusses improvements that can be made.

Section 7.0 describes how to fabricate different versions of the spectrometer and the costs involved. One version uses only commercially available NIMbin electronics and can be assembled without detailed knowledge of electronics. The second version, shown in Figure 1.1, uses electronic circuits developed at PNL to replace NIMbin electronics. The preamplifier, amplifier, and high voltage power supply are small enough to fit onto a single printed circuit board mounted inside the detectors. This version requires a skilled electronics technician to assemble the unit from detailed schematic diagrams and pictorial layouts provided.

The document is not intended to be read from cover to cover. It is divided into different sections that are of interest to persons with different skills and interests. For the health physicist contemplating which spectrometer system to use, Sections 2.0 is suggested reading for an analysis of the different types of neutron spectrometers available, and Sections 3.0 and 4.0 are suggested for a detailed description of the detectors selected for the PNL prototype spectrometer.

For the technician or health physicist making the measurements in the workplace, Section 5.0 on operating the spectrometer is suggested reading. Although not necessary to successfully operate the field spectrometer, the background material in Sections 3.0, 4.0, and 6.0 may help to diagnose problems or limitations that occur during field measurements.

For the health physicist or electronics technician assembling the spectrometer, the detailed information in Section 7.0 on construction techniques and adjustment of the electronics is recommended.

Instructions for setting up and operating the spectrometer are contained in Appendix B. Included are step-by-step procedures intended primarily for the operator who has no prior experience in spectrometry.

There is some overlap of information in the various sections of the report, but this was necessary to ensure that each section provides the information necessary for the intended user. Sufficient detail is provided to allow persons with extensive training in electronics and spectrometry to successfully construct the portable spectrometer. Inexperienced persons can, however, construct the model using commercially available components. Only a little training is required for operating the spectrometer.

2.0 SELECTION OF SPECTROMETERS

A number of practical considerations influence the selection of a portable field neutron spectrometer. Measurements in the workplace are difficult. Workers at PNL have performed neutron measurements in hostile operating environments, including temperatures from -30 to +145 °F, high humidity, vibration, and electrical noise interference. The spectrometer must be small enough to be easily carried and should be moderately priced. However, savings realized by using inexpensive components can be offset by increased downtime, repair, and operating costs. The spectrometer system must be easy to use in the field by operators who may have little training in neutron spectroscopy. In fact, it would be advantageous to design a system to make spectral measurements at the push of a single button. The criterion of ease of use may preclude the use of some types of spectrometers that require extensive adjustment and calibration at each use. Also, the spectrometer should be sensitive enough to perform measurements in a relatively short time, preferably in a few hours, to prevent interference with work schedules. Finally, the spectrometer should not contain toxic or hazardous materials that may hinder its usefulness because of constraints imposed by regulations at a facility.

Many different techniques are available for neutron spectroscopy. Table 2.1 lists the types of spectrometers that are available and their advantages and disadvantages.

All these techniques have inherent problems. No spectrometer 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 from spontaneous fission and alpha-neutron sources (Brackenbush and Endres 1980). Selecting the proper spectrometer system depends not only on its energy range, but also on sensitivity, resolution, complexity of data analysis, portability, and the practical energy limits of the dosimetry system used in the particular facility.

Staff at PNL have experience using all the spectrometers listed above, with the exception of photographic emulsion techniques. Because of time

TABLE 2.1. Neutron Spectroscopy Techniques and Their Advantages/Disadvantages

Detector	Advantages/Disadvantages
Multisphere or Bonner sphere	Useful over a wide energy range, but not very accurate
Proton recoil proportional counter	Can be very accurate, but requires several measurements to adequately cover energy range and careful adjustment of gamma-neutron discriminators
Organic scintillator (NE-213 liquid scintillator)	Very sensitive to fast neutrons, but requires careful adjustment of gamma-neutron discriminator; only useful for fast neutrons with energies above 0.8 MeV if gamma fields are present
Photographic emulsion	One of oldest techniques, but track counting is tedious, and lots of tracks must be counted for statistical accuracy; only useful for energies greater than 0.5 MeV
Activation foils	Limited accuracy at low dose rates because of difficulty in measuring low activity of foils exposed to occupational flux levels
Solid-state nuclear track detectors used with radiator foils	Simple technique, but limited accuracy at higher neutron energy; large numbers of tracks must be counted; problems associated with control of special nuclear materials used in fission foils
^3He and ^6Li sandwich detectors	Good accuracy, but not very sensitive; requires weeks of exposure to obtain statistical accuracy at occupational flux levels
^3He proportional counter	Reasonably accurate, but not very sensitive to high energy neutrons

constraints in development, the PNL field spectrometer was based on existing spectrometers used at PNL. It was designed to include the range of energies involved in processing plutonium; it was not designed for use at the higher energies associated with accelerator operations.

The decision to use a ^3He proportional counter detector for the first prototype field spectrometer was based on the following considerations. First, the ^3He detector is sensitive to neutrons with energies up to at least 5 MeV to measure moderated fission sources. The ^3He detector, however, can

be made very sensitive to obtain neutron energy spectra in fields as low as 0.1 mrem/h, although this can result in detectors that cost over \$2000. Another design criterion was that the spectrometer system be simple enough to make a measurement by pushing a single button. This requires that the data analysis be quite simple, and that the unfolding algorithm used in the analysis of ^3He proportional counter data be easily implemented. Finally, the ^3He detector is self-calibrating using the peak at 764 keV produced by slow neutrons, which are always present in the workplace. This self-calibration feature simplifies the data analysis.

The traditional method for determining neutron quality factors and dose equivalent is to calculate these quantities from the neutron energy spectra; i.e., the neutron flux density as a function of neutron energy. However, quality factors are not defined in terms of incident neutron energy. Quality factors are presently defined as a function of linear energy transfer (LET). Instruments such as tissue equivalent proportional counters (TEPCs) or recombination chambers can be used to determine LET distributions. Thus, quality factors and dose equivalents can also be determined from first principles by using TEPCs with the appropriate algorithms. Agreement between two completely different methodologies (LET distributions derived from TEPC measurements and neutron energy spectra from ^3He spectrometer measurements) lends credibility to the accuracy of the results.

Other types of detectors can be added later if desired. For now, the authors plan to add the multisphere spectrometer analysis to the field spectrometer. When improved pulse shape discrimination circuitry becomes available, the NE-213 liquid scintillator detector will be added.

As stated above, the field neutron spectrometer system is based on existing technology used at PNL. Commercially available components were used when possible. For ease of repair in the field, a modular approach was incorporated so that any defective component could be easily replaced. The PNL spectrometer system consists of two separate modules: 1) a multichannel analyzer (MCA)/computer module and 2) detector modules with ancillary electronics. Each module will be discussed in detail in this report.

The PNL field spectrometer is designed around the MCA/computer module. Many different available minicomputers are powerful enough to handle the spectrum unfolding codes, but it was decided to use a GRiDcase® lap-top portable computer because of its availability at PNL. This computer is IBM PC® compatible so that the software developed can be used in other IBM PC® clones which are widely used. The GRiDcase® computer is used to control an MCA that can make four measurements simultaneously with different detectors. The PNL field spectrometer is designed with electronic circuitry built into the detector modules. This circuitry includes detector, preamplifier, amplifier, and high voltage power supply. Table 2.2 lists the specifications for the PNL field neutron spectrometer system.

TABLE 2.2. Specifications for the PNL Field Neutron Spectrometer System

Element	Specifications
Size of Analysis Module	9 in. x 18 in. x 24 in.
Weight of Analysis Module	40 lb
Power Requirements	110-120 VAC, 50-60 Hz
Detectors Used in Prototype	³ He proportional counter Tissue equivalent proportional counter (TEPC)
Operating Energy Range	50 keV to 5 MeV for ³ He Thermal to 20 MeV for TEPC
Dose Rate Operating Range	0.1 to 100 mrem/h, depending on the size of the detector
Gamma Interference	Rejection of 500:1 photons to neutrons, depending on size and type of detector

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See Appendix A for additional information.

3.0 PRINCIPLES OF ^3He SPECTROMETRY

The principles of operating a ^3He spectrometer are described in this section, including the nuclear principles and techniques used to analyze the data obtained with the spectrometer. The limitations of the present spectrometer are discussed briefly followed by a look at potential future developments.

3.1 NUCLEAR PRINCIPLES

The basis for the use of ^3He as a neutron spectrometer is the nuclear reaction:

Neutrons interact with ^3He to form two charged particles, a proton (light hydrogen), and a triton (hydrogen with two extra neutrons). From it 764 keV of energy is released by the reaction and added to the kinetic energy of the two charged particles. By convention, this reaction is represented as a $^3\text{He}(n,p)\text{T}$ reaction. The 764 keV released by this reaction is called the "Q value" of the reaction and is added to the kinetic energy of incoming neutrons. If the ^3He gas is used as part or all of the fill gas in a proportional counter, the charged particles are easily detected. The pulse produced by the proportional counter will equal the initial energy of the neutron plus the 764 keV released by the nuclear reaction if the triton and the proton deposit all their energy within the proportional counter gas.

The probability of an (n,p) reaction depends on the amount of ^3He present and the energy of the incident neutrons. Figure 3.1 shows the cross section for the $^3\text{He}(n,p)\text{T}$ reaction as a function of neutron energy. Helium-3 has a cross section proportional to the inverse of the velocity of the neutron (or the inverse of the square root of the neutron energy) over a wide range of energies. The $^3\text{He}(n,p)\text{T}$ cross section is 5327 barns at 0.025 eV (2200 m/sec). For energies between 0.025 eV and 1.7 keV, the cross section can be calculated by

FIGURE 3.1. Cross Sections for Neutron Interactions in ^3He Proportional Counters

$$\sigma = \frac{847.3}{\sqrt{E}} \quad (3.2)$$

The cross section, σ , has the units of barns (10^{-24} cm^2); the energy, E , has units of electron volts (Stewart 1974, p. 151). The cross-section data shown in Figure 3.1 is taken from Stewart (1974) for energies below 1 MeV and from Paulsen and Liskien (1974) for energies above 1 MeV. Note that the ^3He detector is very sensitive to low-energy neutrons. Compared to 50 keV neutrons, the ^3He detector is 1800 times more sensitive to thermal neutrons, 290 times more sensitive to neutrons with an energy of 1 eV, and 3.6 times more sensitive to 10 keV neutrons. Calculation of the incident neutron energy spectrum must obviously account for the many orders of magnitude differences in the cross section. Fortunately, for the part of the energy spectrum (50 keV to 5 MeV) that in most cases dominates exposure to workers, the cross section varies only by about a factor of 8.

3.2 NON-IDEAL RESPONSE OF ^3He GAS PROPORTIONAL COUNTERS

An ideal ^3He detector would produce a single peak with an energy equal to the energy of the incident neutron plus 764 keV. However, proportional counters are not ideal detectors. Some of the deviations from the ideal are discussed below.

3.2.1 Gamma Interference

Some of the deviations from an ideal detector are fairly easy to correct, such as gamma ray interference. In a mixed gamma-neutron radiation field, some of the gamma rays will interact with the gas fill or with the walls of the tube to produce electrons that, in turn, will produce pulses. Because of the large Q value of reaction of the neutron with ^3He , the neutron reactions can usually be separated from the gamma reactions (see Figure 3.2).

For some radiation fields, the gamma to neutron dose rates can be 100:1 or greater, so the potential exists for gamma pileup to change the shape of the spectrum collected by the proportional counter. Furthermore, if a high Z fill gas such as argon is used with the ^3He to provide greater stopping power for the charged particles, the cross sections for photoelectric or Compton gamma interactions can become appreciable. High-energy gamma rays undergoing photoelectric or Compton interactions can produce high-energy electrons. If the gas fill is of sufficiently high pressure and the electrons travel down the axis of the tube, enough energy can be deposited to interfere with analysis of the neutron spectrum.

Shielding the tube with a high Z material, such as lead, can significantly reduce the gamma field without unduly perturbing the neutron field. Most gamma shielding materials have small cross sections for interaction with neutrons, and if they do interact by elastic scatter, the energy of the neutron is essentially unchanged.

Therefore, with analytical techniques discussed later and with the use of gamma shielding, the ^3He proportional counter can be used in high gamma-to-neutron radiation fields.

FIGURE 3.2. Pulse Height Distribution for a ^3He Proportional Counter Exposed to Thermal Neutrons

3.2.2 Wall Events

Another way in which ^3He proportional counters deviate from the ideal detector arises from incomplete collection of the charged particle energies. Proportional counters are generally made small so as not to compromise the resolution of the detector from uneven drift times during collection of the charged particles. Having small dimensions means that a fraction of the charged particles created by the ^3He -neutron reaction can strike the wall or the insensitive regions at the ends of the counter before depositing all of their energy in the gas of the tube.

These "wall events" produce a continuum of smaller pulses. Figure 3.2 shows a schematic of results obtained by exposing a ^3He proportional counter to thermal (0.025 eV) or low-energy (1 keV or less) neutrons. If both the triton and the proton are stopped in the counter gas, a full energy peak of 764 keV is produced. If the proton strikes the wall, all of the triton energy (191 of the 764 keV) plus a fraction of the proton energy is often deposited in the gas.

The fraction of energy deposited is a function of the distance from the wall, the energy of the incoming neutron, and the scattering angle, which, in turn, is a function of the source geometry. These wall events produce a sharp edge at 191 keV and a continuum at higher energies. A similar edge occurs at 573 keV with a continuum of higher energies if the triton strikes the wall. The penalty for a high fraction of wall events is greater uncertainty in the corrected spectrum.

Wall events can be minimized by making the dimensions of the tube large compared to the range of the charged particles. However, this compromises the counter resolution (see the discussion of counter resolution in Section 4.0). Alternatively, the ranges of the charged particles can be decreased by using high fill pressures. As discussed above, this involves a tradeoff with increased gamma interference. Whatever the dimension or fill pressures of the tube, the effect of wall events can be corrected out of the neutron spectrum using analytical methods.

3.2.3 Counter Resolution

Gas proportional counters also differ from ideal detectors in that they have finite resolution; i.e., production of protons all with the same energy within the gas would produce a gaussian-shaped response rather than a single channel peak, even if there were no wall events. This is a result of the orientation of the charged-particle track (parallel or across the axis of the tube) and random variations in the drift time during the collection of the charged particles. As mentioned above, the variations in drift time and, therefore, resolution of the counter are a function of the dimensions of the tube. All proportional counters represent a tradeoff between resolution and interference from wall events. In Figure 3.2, the full energy peak at 764 keV has a width of 2.4% or 18 keV at half the maximum height of the peak.

This is commonly referred to as a resolution of 18 keV full-width half-maximum (18 keV FWHM resolution).

3.2.4 Competing Reactions (^3He Recoil)

Unfortunately, the $^3\text{He}(n,p)$ reaction is not the only nuclear reaction that can deposit energy in the gas fill of the counter. The ^3He atoms in the fill gas can also interact with the neutrons traversing the tube by elastic scatter reactions; thus

These "billiard ball" scatter reactions are more probable than the (n,p) reactions for neutron energies above about 50 keV. The cross sections for the $^3\text{He}(n,p)^3\text{H}$ and elastic scatter are shown in Figure 3.1. The scatter reactions, however, deposit less energy in the fill gas than do (n,p) reactions. This occurs because 1) the scatter reaction has no Q value, so the most energy a neutron could impart to the ^3He atom would be all of its kinetic energy, and 2) the laws of conservation of energy and momentum require that no larger fraction of the energy than

$$1 - \frac{(A - 1)^2}{(A + 1)^2} \quad (3.4)$$

can be transferred during a collision where A is the atomic weight of the scattering atom. Thus, for elastic scatter with ^3He ($A = 3$), the maximum energy that could be deposited in the tube is 3/4 of the energy of the incoming neutron. As seen in Figure 3.3, there is a flat continuum of energy below this maximum. The recoil ^3He atoms can also collide with the wall, so that during analysis, the wall effects on the recoils must also be taken into consideration.

Because the desired $^3\text{He}(n,p)^3\text{H}$ reaction has a Q value of 764 keV, only neutrons with energies greater than 1.02 MeV can produce recoils with enough energy to be confused with the (n,p) reaction. As an example, Figure 3.3 shows the response of an unshielded ^3He proportional counter exposed to nearly monoenergetic neutrons with an average energy of 660 keV produced by a

FIGURE 3.3. Response of an Unshielded ^3He Proportional Counter Exposed to 660 keV Monoenergetic Neutrons

Van de Graaff accelerator at PNL. Because neutrons were scattered and moderated by the concrete floor and walls, a thermal or low energy peak produced at 764 keV can be used for energy calibration. Note that, for the monoenergetic 660 keV neutrons, the maximum energy of the recoil neutrons is below the thermal peak.

The effect of recoils cannot be mitigated by shielding or other physical manipulation of the proportional counter because the ratio of (n,p) to scattering cross sections is an intrinsic property of the ^3He isotope. For discussion of analytical techniques to correct for scatter, see Section 3.3 on analytical techniques.

3.2.5 Pulse Pileup

If two events occur nearly simultaneously in the proportional counter, the pulses can be summed together to produce a larger pulse, which can be mistaken for an event produced by a higher-energy neutron. Figure 3.4 shows how two neutron interactions, labeled A and B, can produce a pulse larger than a single event, labeled C. In Figure 3.4, the resolving time, t , is defined as the minimum time interval in which two separate events can be measured without overlap. The resolving time is usually determined by the time constants of the shaping amplifier, which is often dictated by the minimum pulse width that can be accepted by the MCA used to record data. Typically, the shaping amplifier time constants are 1 to 2 μs which produce resolving times of 4 to 8 μs .

The probability that two events will occur within a specified time can be estimated mathematically. The particular branch of mathematics that describes this process is called Poisson statistics. If γ is the count rate

FIGURE 3.4. Pulse Pileup Resulting When Two Pulses Occur Within the Resolving Time of the Spectrometer System

in the detector in counts per second, t is the resolving time of the counter, and n is the number of interactions in the time interval t , then the probability, p , of n interactions is

$$p_n(t) = e^{-\gamma t} (\gamma t)^n / n! \quad n=0,1,2,3\dots \quad (3.5)$$

Table 3.1 shows the fraction of events that will count in coincidence as calculated by Equation (3.5) for $n = 2,3,\dots$, using a resolving time of $8 \mu s$.

In ^3He spectroscopy, pileup can be a problem in two circumstances: 1) when the gamma-to-neutron flux ratios are over 50:1 so that the pulse-summing is the addition of gamma pulses with neutron pulses, or 2) when the thermal component of the neutron flux is high. Because the thermal cross section is roughly a factor of a thousand higher than cross sections in the low keV part of the neutron spectrum, a high thermal component of the neutron flux will cause pileup. It is easy to determine whether thermal pileup is effecting the measured spectrum by looking at energies of roughly twice the thermal peak. A sum peak of two thermal neutrons will appear at or slightly below 1528 keV depending on how completely the peaks are summed.

To avoid pulse pileup problems, the overall reaction rate in the proportional counter must be kept below levels where serious distortion of the spectrum occurs. This can be accomplished in a variety of ways:

TABLE 3.1. Pulse Pileup Rate Calculated for an $8\text{-}\mu s$ Resolving Time

<u>Count Rate, counts/sec</u>	<u>Coincidence Rate, counts/sec</u>	<u>Fraction of Events in Coincidence</u>
100	0.000032	3.2×10^{-7}
1,000	0.032	3.2×10^{-5}
5,000	3.8	7.7×10^{-4}
10,000	30	3.0×10^{-3}
20,000	218	1.1×10^{-2}
50,000	2,700	5.3×10^{-2}
100,000	18,000	1.8×10^{-1}

- make measurements in lower-flux fields
- use proportional counters with a small amount of ^3He
- cover the tube with lead shielding for reducing gamma pulse-summing
- cover the tube with cadmium shielding for thermal neutron pileup
- use electronic pulse-shape analysis to reduce pileup
- analytically correct counts using Poisson statistical methods.

In future efforts, analytical techniques will be developed to correct for pileup problems. For the current spectrometer and software, 1/8-inch lead gamma shields and, if necessary, a 40-mil cadmium shield can be added to reduce the thermal neutrons to negligible levels. In situations where there are large numbers of epithermal energy neutrons (such as nuclear reactors), an additional shield containing boron will aid in reducing pileup from the neutrons with energies below 1 keV.

3.3 DATA ANALYSIS TECHNIQUES

The techniques described in the following sections are used to analyze the data from the ^3He proportional counter to obtain an approximate neutron energy spectrum. From this approximate spectrum, dose equivalent, average energy, and average quality factor, Q , are calculated.

Bare and lightly moderated fission sources are the origin of most of the exposure that workers in DOE facilities receive. Essentially all neutron dose equivalent arises from that part of the energy spectrum above 50 keV. For this reason, and to provide a system that is as easy as possible to operate, the contributions to dose equivalent rate, to average Q , and to average energy are ignored for neutrons with energies below 50 keV. Methods are available to measure, analyze, and include the contribution of the neutrons below 50 keV (Brackenbush, Reece, and Tanner 1984) and may be included as an option in future upgrades.

To accurately determine the neutron energy spectra, the number of slow neutrons reaching the counter must be controlled to prevent pileup. As discussed in Section 3.2.5, this can usually be accomplished by covering the counter with cadmium shields. Also, the gamma contribution to the counter signal must be controlled. The gamma contribution can usually be brought to reasonable levels by shielding the counter with 1/8 in. of lead or by

measurements in radiation fields having relatively low dose equivalent rates (tens of millirem per hour).

The analysis of the proportional counter response involves several steps. The energy of the fast neutrons can be found by subtracting 764 keV (the Q value of the $^3\text{He}(n,p)^3\text{H}$ reaction) from the total energy deposited in the ^3He detector. As pointed out in Section 3.2.2, some of the triton and protons do not deposit all of their energy within the gas in the proportional counter, but collide with the wall and transfer their energy to the wall of the counter producing a smaller pulse from the detector. Some method must be devised, therefore, for correcting for these wall events. One possibility is to empirically determine the wall event distribution by measurements with monoenergetic neutrons. However, this strategy is difficult, time-consuming, and expensive. Some work has been done toward deriving analytical expressions to estimate wall events, but all analytical methods suffer from some approximation and are applicable only to a single-source geometry.

Researchers at PNL have written a Monte Carlo computer code called WALL5 that calculates the number of wall events and the distribution of energy deposition in the sensitive volume of an arbitrarily dimensioned cylindrical proportional counter as a function of neutron energy and fill gas composition. The output of the WALL5 code is designated as the "response function." Basically, the response function relates the energy deposited in the proportional counter to the energy of the interacting neutron. This relation includes both the wall events and ^3He scattering events. See Figure 3.5 for a graph of the response function for isotropic neutron radiation fields.

Using the WALL5 code, response functions have been generated for beam, isotropic, and point geometries. Several second-order events have not been included in the WALL5 algorithm, including subtle differences in ionization for different types of ions and rebound of the ions after striking the tube wall. For equal energy depositions, the ^3He recoil ions produce about 10% more ionizations than hydrogen ions and, therefore, appear at 10% higher energies than predicted by assuming equal ionization per energy absorption. The response functions have been empirically corrected so that fission

FIGURE 3.5. Response Function for ^3He Detector

spectra and monoenergetic neutrons produced by the PNL Van de Graaff are correctly analyzed. The principle and operation of the WALL5 Monte Carlo code will be published in a separate report at a future date.

If the response function is known, the incident neutron spectra can be calculated by solving the integral equation convoluting the response function and the measured spectra. Various techniques exist for solving these types of equations, including matrix inversion and deconvolution using Fourier transforms. However, a simple "stripping" algorithm can be used by a micro-computer to calculate answers in a minute or two. The disadvantage to this technique is that statistical uncertainty errors are propagated to the lower-energy portion of the spectrum from the higher-energy portion.

The stripping algorithm is straightforward. Consider the highest energy bin in the collected spectrum. Because scatter events always produce lower

energies, if the range of the collected spectrum is comparable to the range of the real incident spectrum, then all of the events in the highest channel must be result from the (n,p) reaction. From the response function, we know what fraction of the (n,p) events deposit their full energy, so that we can calculate how many (n,p) reactions actually took place in the tube by dividing the counts in the highest channel by the response fraction. Knowing the total number of (n,p) reactions for this (the highest) energy, the rest of the response function for this incident neutron energy can be used to predict the effects at lower energy from wall events and scattering events. These effects are subtracted from the collected spectrum energy bin by energy bin. Now consider the next channel below the highest energy channel. Because the effects of wall events and recoils have been subtracted, the counts in this channel must be from (n,p) reactions. The total number of (n,p) reactions can be found, and corrections of all the lower-energy channels are made. By repeating this technique for all of the lower energy channels, the incident neutron spectrum can be calculated, limited only by the uncertainty in the counts.

More formally, the mathematical algorithm is

$$C'(j) = C(j) - \sum_{i=j+1}^{j_{\max}} C'(i) W(i,j) \quad (3.6)$$

where $C'(j)$ is the count in energy bin j corrected for wall and scatter events, $C(j)$ is the uncorrected count in energy bin j (the raw data), and $W(i,j)$ is the response function for incident neutron energy j on energy bin i . As indicated in the above text, the corrected count for the highest energy bin used for each iteration of the stripping algorithm is $C(j)/W(j,j)$.

This algorithm is implemented by a computer code we have written called HE5. After the stripping process is complete, the corrected spectrum contains the number of (n,p) reactions for each energy bin. The HE5 code then divides the number of events in each energy bin by the appropriate macroscopic cross section to derive the neutron flux density incident on the tube as a function of energy, as shown:

$$\phi(E) = \frac{C'(E)}{N \sigma(E)} \quad (3.7)$$

where $\phi(E)$ = neutron fluence (n/cm²) at energy E

$C'(E)$ = corrected counts in a given energy bin

E = average energy of the bin

N = total number of ³He atoms in the sensitive volume of the proportional counter

$\sigma(E)$ = ³He(n,p)T cross section at energy E.

Once the differential fluence, $\phi(E)$, is known, the HE5 code calculates the fractional dose equivalent for each energy bin. These values are then summed to give total neutron fluence and dose equivalent, along with average energy and average quality factor. The fluence-to-dose equivalent conversion factors and average quality factors as a function of neutron energy are calculated using the formulas given in the American National Institute (ANSI) publication, American National Standard Neutron and Gamma-Ray Flux-to-Dose-Rate Factors, ANSI/ANS-6.1.1-1977 (ANSI 1977).

4.0 THEORY OF OPERATION OF TISSUE EQUIVALENT PROPORTIONAL COUNTERS

As stated earlier, TEPCs were selected because they provide an absolute measure of absorbed dose in a tissue-like material. With appropriate algorithms, they also provide an estimate of neutron quality factor. For fission energies, existing algorithms for determining quality factors from the absorbed dose distributions measured by the TEPC are reasonably accurate. An additional advantage is that, even if quality factors are redefined in the future, the TEPC provides a measure of the absorbed neutron dose and sufficient information to calculate the new or redefined quality factors. The TEPC also has the advantage of being self-calibrating. This may be of great benefit to DOE facilities with no access to a standard neutron source that has been calibrated by the National Bureau of Standards (NBS).

Section 4.0 discusses the theoretical basis for determining absorbed dose, quality factors, and dose equivalent. Included are details about the construction of TEPCs, how they operate, the algorithms involved in determining quality factors, and the measured accuracy of the TEPC.

4.1 THEORY OF RADIATION INTERACTIONS

Many health physicists are not familiar with the microdosimetric concepts used in the analysis of data from TEPCs. Therefore, the following explanation of the terms used may be appropriate. A more complete explanation of terminology is given in ICRU Report 36, Microdosimetry (ICRU 1983).

Energy deposit, e_i - The energy deposit is the energy deposited in a site by a single radiation interaction. It is the difference between the energy of the incident ionizing particle (exclusive of rest mass) minus the sum of all energies of all ionizing particles leaving the interaction (exclusive of rest mass) plus the changes in rest mass of all atoms and particles involved (the so-called Q value of the reaction). The energy deposit is a stochastic quantity that has units of Joule (J) or electron volts (eV).

Energy imparted, e - The energy imparted to the mass in a volume is simply the sum of energy deposits within the volume. The energy imparted is also a stochastic quantity having units of Joule (J) or electron volts (eV). Note

that the energy imparted may result from one or more statistically independent particle tracks.

Lineal energy, y - The lineal energy (y) is the quotient of the energy imparted by a single energy deposition event to matter in a volume (e) divided by the mean chord length (l) in that volume. Lineal energy is a stochastic quantity with units of Joules per meter (J/m) or kiloelectron volts per micrometer (keV/ μ m). The mean chord length in a volume is the average or mean of all randomly oriented chords within the volume. For convex bodies, the mean chord length (l) is the quotient of 4 times the volume (V) divided by the surface area (S) of the body. It is important to note that y is defined only for single energy-deposition events. Energy-deposition events occur with a distribution of lineal energies. The value of the distribution function, $F(y)$, is the probability that the lineal energy is equal to or less than y . The *lineal energy distribution* or probability density, $f(y)$, is the derivative of $F(y)$ with respect to y . The lineal energy distribution, $f(y)$, is independent of the absorbed dose or dose rate.

Linear energy transfer (LET) or L - The linear energy transfer is the amount of energy transferred per unit path length of an ionizing particle. It has units of Joule per meter (J/m) or kiloelectron volts per micrometer (keV/ μ m).

Event size, Y - The event size is a concept closely related to lineal energy. The event size is the energy imparted to a sphere divided by the diameter of the sphere. For a sphere, the mean chord length is two-thirds of the diameter.

Lineal energy (y) and linear energy transfer (LET) are closely related. Consider the path of a recoil proton produced by a 1 MeV neutron, as shown in Figure 4.1. The dots in the figure represent ionizing events produced by the passage of the proton and its delta rays. The value of LET is constant over the short segment of the particle path shown in the figure. However, as can be readily seen, the value of lineal energy depends on which microdosimetric volume is chosen. This is observed experimentally; i.e., particles with a constant LET traversing a proportional counter operated at very low gas pressures produce a distribution of event sizes. Lineal energy is a microdosimetric quantity that represents the actual amount of energy

FIGURE 4.1. Representation of a Short Segment of the Track of a Recoil Proton Produced by a 1 MeV Neutron

deposited in a microscopic site; it is the microscopic analog of LET. Lineal energy can be physically measured by devices such as TEPCs. Linear energy transfer is a macroscopic quantity that cannot be easily measured. The value for LET represents the average value for the energy loss per unit path length, and thousands of paths must be considered to obtain an accurate average. Under the assumptions that the particles travel in straight lines and LET is nearly constant over small segments, it is possible to mathematically convert from either quantity to the other, as illustrated in Appendix B of a report issued by a Joint Task Group of ICRU and ICRP, ICRU Report 40 (ICRU and ICRP 1986).

The basic concept of a TEPC is shown in Figure 4.2. Typically, the TEPC consists of a hollow sphere of tissue equivalent (TE) plastic filled with tissue equivalent gas. The cavity inside the sphere is the sensitive volume of a proportional counter. Several different configurations are possible. In one version, a single wire is used for the anode of the proportional counter. In another version, called the Rossi counter, a fine helix operated at an intermediate potential surrounds the anode wire to make the electric field more nearly constant, thus giving a more nearly uniform gain along the anode. Unfortunately, the helix makes the counters more sensitive to vibration. Single-wire counters are more rugged and are usually used for

FIGURE 4.2. Simplified Cross-Sectional View of a Spherical Tissue Equivalent Proportional Counter

measurements in the workplace. Spherical counters with internal diameters ranging from 1/2 in. to 5 in. are commercially available.(a)

Unlike the typical proportional counter, the gas pressure in the TEPC is very low, usually a few torr, so that the mass of gas in the hollow sphere has the same mass stopping power as a 1-micrometer sphere of tissue at unit density. The equivalent diameter of a gas-filled TEPC is the diameter of a unit-density sphere that has the same mass as the gas inside the TEPC. The gas pressure is usually adjusted to give equivalent diameters of 0.5 to 10 μm in tissue.

The compositions of tissue equivalent gases and Shonka A-150 tissue equivalent plastic are given in Table 4.1. It is evident that the compositions of these materials are not exactly equivalent to tissue, which is mostly water. In most plastics, the amount of carbon and oxygen are reversed. This is of little consequence for most neutron energies, except for the resonances in charged particle production that occur at about 4.5 MeV and at 16 to 17 MeV.

(a) See Appendix A for additional information.

TABLE 4.1. Compositions of Tissue Equivalent Materials Used in Tissue Equivalent Proportional Counters (TEPCs) (a)

Material	Percent of Element (%)										
	H	C	N	O	F	Na	Mg	P	S	K	Ca
ICRU Muscle Tissue	10.2	12.3	3.5	72.9	-	0.08	0.02	0.2	0.5	0.3	0.007
A-150 Muscle Equivalent Plastic	10.1	77.6	3.5	5.2	1.7	-	-	-	-	-	1.8
Methane TE Gas	10.2	45.6	3.5	40.7	-	-	-	-	-	-	-
Propane TE Gas	10.3	56.9	3.5	29.3	-	-	-	-	-	-	-

(a) Data from Appendix C of ICRU Report 36, Microdosimetry (ICRU 1983).

Neutrons or other types of ionizing radiation interact with the Shonka A-150 tissue equivalent plastic wall to produce charged particles, which then traverse the gas cavity. The gas pressure is so low that most particles have a nearly constant LET in traversing the cavity. If Bragg-Gray conditions are satisfied (i.e., if electronic equilibrium exists), if the wall thickness is greater than the range of the secondary particles, and if the walls and gas have nearly the same composition, then the dose in the cavity is a very close approximation to that in the solid tissue equivalent material. If it is assumed that the ionization produced in the detector is proportional to the energy deposited in the gas cavity, this value of energy deposition can be divided by the mass of the gas to determine the absorbed dose (energy per unit mass).

4.2 METHODS OF CALIBRATION

The calibration of a TEPC relates the pulse height distribution from the proportional counter to energy deposition in the counter. At least two methods will accomplish this.

The first method is to bombard the gas cavity with particles of known energy. Some of the commercially available TEPCs have built-in ^{244}Cm alpha calibration sources operated by a simple shutter mechanism. When the shutter is open, alpha particles pass through a small hole in the tissue equivalent plastic wall and traverse the diameter of the counter. Because the initial energy of the alpha particles, the path length, and the amount of material along the path length are known, the energy loss in the gas cavity per unit path length can be calculated. This value can then be related to the centroid of the peak produced by alpha pulses, as recorded by a MCA. This result is the energy deposition per unit path length per MCA channel.

The second method relies on built-in calibration using the so-called "proton edge" or "proton drop point." Consider the case where a TEPC is irradiated by fast neutrons. The neutrons produce recoils with a continuum of energies and LET values. Protons with the highest LET values that traverse the diameter of the counter will deposit the maximum possible energy. This results in the so-called proton edge. These energy deposition values have been measured experimentally for methane-based tissue equivalent gas by Glass and Samsky (1967). In the experiment, monoenergetic protons produced by a Van de Graaff accelerator irradiated a gas cavity with a known mass. The energy of the proton as it exited the gas cavity was measured using a surface barrier detector. Thus, Glass and Samsky directly measured the energy loss in the gas cavity filled with methane-based tissue equivalent gas and related this to the path length in the gas cavity. Because of straggling, the proton edge is not perfectly sharp. The proton drop point, as defined by Glass and Samsky, is the point of inflection on the dose distribution curve. For site sizes with an equivalent diameter varying between 0.5 to 10 micrometer, the proton drop point only varies between 90 and 103 keV/ μm , as shown in Table 4.2. The real problem with using the proton drop point for energy calibration is that good statistical accuracy requires at least 20 mrem to obtain a reasonable estimate of the point of inflection.

TABLE 4.2. Relationship Between the Proton Drop Point Used for Energy Calibration and the Site Size in a Tissue Equivalent Proportional Counter

Equivalent Diameter, μm	Energy Deposition, $\text{keV}/\mu\text{m}$
0.3	104
0.5	103
1.0	101
2.0	98
5.0	90

Source: Glass and Samsky 1967

4.3 DATA ANALYSIS

An MCA is usually used to record the distribution of pulse heights from a TEPC. Figure 4.3 shows a typical spectrum as recorded by a TEPC operated with a $1\text{-}\mu\text{m}$ equivalent diameter.

4.3.1 Energy Calibration

The energy calibration relating lineal energy to channel number in the MCA is determined using the proton edge method described in Section 4.2. The data is typically recorded with the proton edge occurring near channel 200 to 300 in a 2048-channel spectrum. The counts per channel are multiplied by the channel number to obtain a distribution proportional to the dose distribution. A Fourier smoothing technique is used to smooth the data (Aubanen and Oldham 1985). A digital derivative filter is then applied to find the largest negative derivative. This corresponds to the point of inflection on the dose curve, which is the proton drop point. Knowing the dimensions of the counter and the gas pressure allows the equivalent diameter of a sphere of tissue of unit density to be calculated. This value can be used to determine the energy calibration in terms of keV per channel.

One problem that became evident during testing of the TEPC was that the degree of smoothing influences the proton drop point. When a small amount of data is acquired, it is desirable to have a high degree of smoothing to suppress random oscillations in the derivative that are caused by statistical fluctuations. As more data are acquired, less smoothing is desired. The present version of the analysis code has a Fourier smoothing function that is

FIGURE 4.3. A Typical Spectrum as Recorded by a TEPC Operated with a 1-μm Equivalent Diameter

a compromise. If the TEPC is exposed to several hundred mrem, the data are over-smoothed, and the point of inflection is picked at a lower channel. This results in an energy calibration value that is too high thus producing an overestimate of the quality factor and dose equivalent rate.

An additional problem in some older TEPCs is that the gas gain deteriorates over a period of several days to a week. Small amounts of oxygen, water vapor, plasticizer, or other electronegative gases diffusing out of the tissue equivalent plastic can cause a rapid deterioration in the counter gas. Different tests were made by placing a TEPC at a fixed distance from a ^{252}Cf source and measuring the dose equivalent rate over a period of 3 weeks. When the counter was first filled, it underestimated the accepted dose equivalent rate value by 4%. After 3 weeks, the gain of the counter decreased by 50% and the resolution deteriorated. This TEPC then overestimated the dose equivalent rate by 12% to 16%. Much of the apparent increase could be attributed to the smoothing algorithm picking a low value for the proton drop point. The loss of resolution tended to place a significant number of events above the proton edge, which increased the quality factor value. This points out the necessity of testing for changes in the gas gain over time. Recently manufactured TEPCs generally do not exhibit this changing gas gain problem, because the A-150 plastic has been outgassed during manufacture.

4.3.2 Determination of Absorbed Dose

In mixed radiation fields, it is possible to separate neutron and photon events recorded by a TEPC on the basis of lineal energy or pulse height by selecting the minimum, as shown in Figure 4.3, as a threshold. This threshold normally occurs at a lineal energy of about $15 \text{ keV}/\mu\text{m}$. Events registering above the threshold are considered to result from neutron interactions; events below the threshold are considered to be produced by photons. Some overlap between the two types of events will occur, but the resultant error will be less than a few percent.

Once the energy calibration and separation between neutron and photon induced events has been obtained, it is possible to determine the absorbed neutron dose. The absorbed neutron dose, D , is determined from the following formula:

$$D = (c/\rho V) \sum N(E) E \quad (4.1)$$

where $N(E)$ = number of events of energy E as measured by the TEPC

E = energy deposited expressed in terms of the channel number

ρV = product of gas density times cavity volume (or mass of the gas in the cavity)

c = constant of proportionality relating the energy deposition to channel number (Rossi 1968).

The accuracy with which TEPCs can measure neutron absorbed dose is demonstrated in Figure 4.4. Several different spherical TEPCs were exposed to monoenergetic neutrons produced by Van de Graaff accelerators. The fluence was measured using a precision long counter (DePangher and Nichols

FIGURE 4.4. Ratio of Neutron Dose Measured by the TEPCs to the Kerma Calculated from Fluence Measurements

1966) or fission counter. For these free-in-air exposures, the absorbed neutron dose in a small tissue site is closely approximated by the kerma. The kermas were calculated using published conversion factors (Caswell, Coyne, and Randolph 1980). On the average, the TEPC measurements agree within 3% with a standard deviation of 9% for neutron energies between 100 keV and 7.5 MeV. Because of experimental difficulties, such as non-uniform illumination of the long counter, the fluence measurements may not be as accurate as the kerma measurements made by the TEPCs.

4.3.3 Determination of Quality Factors

The most difficult problem in analyzing the data from a TEPC measurement is converting absorbed dose to effective or average dose equivalent. At the present time, quality factors are defined as a function of LET (NCRP 1971b). The definition of this relationship is given in Table 4.3.

Tissue equivalent proportional counters measure lineal energy, i.e., the energy deposited in the site divided by the mean chord length of the site. For a spherical proportional counter, the mean chord length is two-thirds of the diameter. Problems occur in attempting to convert from lineal energy distributions to linear energy transfer distributions, as discussed in Sections 4 and 5 of ICRU Report 36, Microdosimetry (ICRU 1983). A paper by Hartmann, Menzel, and Schuhmacher (1981) discusses various algorithms for

TABLE 4.3. Relationship between Quality Factor and Linear Energy Transfer

<u>Quality Factor</u>	<u>Linear Energy Transfer, keV/μm</u>
1	<3.5
2	7
5	23
10	53
20	>175

Source: NCRP (1971b, p. 81).

determining quality factors from TEPC measurements. Additional information on determining mean quality factors from TEPC data is given on p. 67 of ICRU Report 36 (ICRU 1983). The theoretical basis for algorithms for relating lineal energy to LET was developed almost 20 years ago by Albrecht Kellerer (1969). Equation (52) of Kellerer's paper relates LET and lineal energy by the equation

$$\bar{y}_D = (\delta_2/\bar{l}) + \bar{L}_D (\overline{l^2})/(\bar{l}) \quad (4.2)$$

where $\bar{y}_D$ = the "dose mean" of the event spectrum measured by the TEPC (i.e., the average lineal energy or first moment of the dose distribution)

δ = the "energy mean" loss per collision and is given by Equation (43) of Kellerer (1969)

$\bar{l}$ = the mean chord length in the cavity

$\overline{l^2}$ = the mean of the square of the chord length distribution in the cavity

$\bar{L}_D$ = the dose mean linear energy transfer.

For practical purposes, the first term of Equation (4.2) can be ignored. For a sphere, the mean chord length is two-thirds of the diameter. Thus, Equation (4.2) reduces to

$$\bar{y}_D = (9/8) \bar{L}_D \quad (4.3)$$

Consider the case of a single LET value corresponding to a quality factor value derived from Table 4.3. In this case the quality factor can be found by setting

$$\bar{L}_D = (8/9) \bar{y}_D \quad (4.4)$$

Because of the linear and additive relationship, this process can be repeated for all values of L to determine a dose weighted average quality factor, Q:

$$\bar{Q} = (1/D) \int Q(L) D(L) dL, \quad (4.5)$$

where $Q(L)$ is the quality factor interpolated from the data in Table 4.3, $D(L)$ is the differential absorbed dose as a function of linear energy transfer (derived by setting $L = (8/9) y$), and D is the total absorbed neutron dose.

4.3.4 Determination of Dose Equivalent

The dose equivalent is then found by

$$H = \bar{Q} D \quad (4.6)$$

where $\bar{Q}$, the average quality factor, is determined by Equation (4.5) and D is determined by Equation (4.1).

How do the quality factor and dose equivalent determined by TEPC measurements for a small tissue site relate to the whole body average quality factors and dose equivalents currently used in radiation protection? Over 20 years ago, Snyder, Auxier, Jones, and co-workers at Oak Ridge National Laboratory (ORNL) calculated average quality factors that were applicable for whole body neutron irradiations (Auxier, Snyder, and Jones 1968). The human body was modeled as a cylinder of soft tissue, 30 cm in diameter. A parallel beam of monoenergetic neutrons was assumed to strike the cylinder normal to its axis. A Monte Carlo computer code was used to determine neutron transport and photon production at various small volumes inside the phantom. The Monte Carlo code calculated the production of charged particle secondaries and the LET distribution of these secondary radiations.

From the definition of quality factor as a function of LET, it was possible to calculate the dose equivalent for each of the volume elements in the cylindrical phantom according to the simple equation $H(L) = Q(L) D(L)$, where the dose equivalent and absorbed dose were calculated as a function of LET. All the contributions to dose equivalent and dose from neutron recoils and activation gammas can be summed together to determine a single dose equivalent or absorbed dose for a given volume element. For a given neutron energy, the Oak Ridge group selected the highest value of dose equivalent that occurred in any volume element in the cylinder. This value represented

the whole body. Note that this procedure also provided average quality factors, which were calculated as the ratio of H/D (the dose equivalent divided by the absorbed dose) in the volume element with the highest value. A review of these calculations is given by Auxier, Snyder, and Jones (1968).

These values calculated for the cylindrical phantom are applicable to the whole body. They are the values for fluence-to-dose equivalent conversion factors and average quality factors that are listed in NCRP Report 38, Protection against Neutron Radiation (NCRP 1971a), and that are used in DOE Orders. Several problems occur when using these values. For polyenergetic neutron spectra, the fluence-to-dose equivalent conversion factors are added together for the various energies. Because the maximum values of dose equivalent may occur at different depths in the phantom, this sum will always be conservative. At low neutron energies, below about 10 keV, the primary mechanism for neutron interaction is the production of activation gammas from $H(n,\gamma)D$ reactions. These activation gammas are included as part of the neutron dose equivalent, although a photon dosimeter on the surface of the body would measure some of the gammas and include them in the gamma dose. Finally, no effects of irradiation geometry are included in the conversion factors or average quality factors; all radiations are considered to be normally incident to the phantom. All of these effects result in conservative "cap" values for whole body dose equivalent and average quality factors.

This conservatism is not reflected in TEPC measurements. The TEPC determines the quality factor at a depth corresponding to the thickness of the tissue equivalent plastic walls, which is typically 1/8 in. thick. However, many algorithms for quality factor tend to slightly overestimate quality factors, so that TEPC measurements for fission energies are remarkably close to the values calculated from neutron energy spectra. Moreover, in a TEPC, it is not possible to distinguish between external gamma rays and gamma rays produced by neutron capture reactions. Therefore, all gamma rays are excluded from analysis. For fission energies, this does not present a problem. However, for neutrons with energies below 10 keV, the major contribution to neutron fluence-to-dose equivalent conversion factors originates from capture gamma rays from hydrogen. A more detailed discussion is given in an article by Brackenbush et al. (1984).

4.4 PROPOSED CHANGES IN NEUTRON QUALITY FACTORS

At the present time, apparently conflicting recommendations exist for changing both the values and methods used to determine quality factors and dose equivalent. In Publication 51, Data for Use in Protection Against External Radiation (ICRP 1987), the ICRP gives specific guidance on appropriate values for average or effective neutron quality factors. The NCRP also has recommended the doubling of neutron quality factor values in Report No. 91, Recommendations on Limits for Exposure to Ionizing Radiation (NCRP 1987).

However, simply doubling the existing values used for neutron quality factors may not be appropriate. As noted in Section 4.3, the existing quality factor values are based on the Monte Carlo calculations of Auxier, Snyder, Jones, and coworkers at Oak Ridge (Auxier, Snyder, and Jones 1968). For neutrons with energies below about 10 keV, a significant contribution to the quality factor value originates from activation gamma rays produced by the absorption of neutrons by hydrogen. If existing quality factors for low-energy neutrons are doubled, quality factors for these activation gamma rays are in essence doubled. Also, quality factors for all ionizing radiations are currently defined as a function of linear energy transfer. Simply doubling the values for average quality factor derived from the Oak Ridge calculations is inconsistent with the existing definition of quality factor as a function of LET. Obviously, there is a great deal of discussion concerning what neutron quality factors should be. To date only Japan has formally adopted the recommendations of the ICRP or the NCRP to double quality factors.

One recent recommendation is apparently consistent with doubling quality factors for fast neutrons. In ICRU Report 40, The Quality Factor in Radiation Protection (ICRU and ICRP 1986), a Joint Task Group composed of members of the ICRU and the ICRP recommended defining a relationship between quality factor and lineal energy based on a 1- μm -dia spherical volume of tissue. This recommendation uses a procedure similar to that developed by Zaider and Brenner (1985). This relationship is shown in Figure 4.5 and is given by the equation

FIGURE 4.5. Quality Factor, $q(y)$, Redefined as a Function of Lineal Energy, y , for a 1- μm -Dia Sphere of ICRU Tissue

Source: ICRU and ICRP 1986, p. 10

$$q(y) = (a_1/y)[1 - \exp(-a_2 y^2 - a_3 y^3)] \quad (4.7)$$

with coefficients having the values of

$$a_1 = 5510 \text{ keV}/\mu\text{m}$$

$$a_2 = 5 \times 10^{-5} \mu\text{m}^2/\text{keV}^2$$

$$a_3 = 2 \times 10^{-7} \mu\text{m}^3/\text{keV}^3.$$

Even an irradiation by monoenergetic radiations or particles with a constant LET will produce a distribution of lineal energies. Thus, a dose-weighted average quality factor can be defined:

$$\bar{q} = (1/D) \int d(y) q(y) dy \quad (4.8)$$

where $d(y)$ is the distribution of absorbed dose in lineal energy, y , and $q(y)$ is the quality factor defined in Equation (4.7). Once the (dose-weighted)

average quality factor is determined, the dose equivalent can be determined by

$$H = \bar{q} D \quad (4.9)$$

The quantities determined in Equations (4.8) and (4.9) are determined by the energy spectrum at the point of interest and not by the incident energy spectrum outside the body or phantom. Using the definition of quality factor from Equation (4.7), it is possible to determine the dose-weighted average quality factors from Equation (4.8) for monoenergetic radiations. The dose-weighted effective quality factors, $\bar{q}$, are given in Figure 4.6 for monoenergetic neutrons (ICRU and ICRP 1986, p. 11).

FIGURE 4.6. Dose-Weighted Effective Quality Factor, $\bar{q}$, Calculated as a Function of Neutron Energy for Monoenergetic Neutrons

Source: ICRU and ICRP 1986, p. 11

Redefining quality factors as a function of lineal energy results in adopting variable quality factors for all radiations, including photons. The practical difficulties of measuring variable quality factors for photons may impede the acceptance of the recommendations in ICRU Report 40 (1986).

Dose distributions can be measured as a function of lineal energy, $d(y)$, by using TEPCs. Thus, it is possible to determine dose-weighted average quality factors and dose equivalents from first principles. Furthermore, it is possible to demonstrate that the dose-weighted average or effective quality factors derived from Equations (4.7) and (4.8) give values that agree substantially with proposals to increase quality factors by a factor of 2 for fast neutrons. However, at very high energies above 20 MeV, the increases are less than a factor of 2. It is important to note that these quality factor increases are defined at the point of interaction in tissue; they do not apply to quality factor values averaged over the whole body.

In ICRP Publication 26, the ICRP introduced a new system of dose limitation for stochastic effects that allows the combination of internal and external exposures for occupationally exposed workers (ICRP 1977). In paragraphs 104 to 112, the ICRP introduces the concept of tissue-weighted effective dose equivalent, H_e , which is the summation of the products of the dose equivalent determined for designated tissues, H_T , multiplied by a weighting factor, W_T :

$$H_e = \sum W_T H_T \quad (4.10)$$

The effective dose equivalent methodology takes into account the radiosensitivity of various tissues in the body, as well as the attenuation and degradation of energy of radiations in reaching the designated tissues. In ICRP Publication 51, Data for Use in Protection Against External Radiation (ICRP 1987), the ICRP gives details of calculated values of effective dose equivalent for various irradiation geometries and neutron energies. Using this same methodology, workers at PNL have calculated effective dose equivalent values using the quality factors redefined as a function of lineal energy. The results of these calculations are shown in Figure 4.7. The curves in the figure compare the values of the present fluence-to-dose

FIGURE 4.7. Comparison of Conversion Factors for Existing Fluence-to-Dose Equivalent Factors and Fluence-to-Effective Dose Equivalent Factors Based on the Redefinition of Quality Factor, Q , as a Function of Lineal Energy

equivalent conversion factors obtained from the Monte Carlo calculations of the Oak Ridge group for a cylindrical phantom to the PNL Monte Carlo calculations using the effective dose equivalent methodology with an anthropomorphic phantom and quality factors redefined as a function of lineal energy.

The values shown in Figure 4.7 are calculated for an irradiation by an anterior beam of monoenergetic neutrons, which results in the most conservative values for effective dose equivalent. The figure indicates that the effects of doubling quality factors at the tissue level is mitigated by the adoption of effective dose equivalent methodology. Note that it is also possible to calculate an effective quality factor applicable to the whole body effective dose equivalent, but the authors are hesitant to add yet another quality factor to an already confused situation.

In conclusion, quality factors can be redefined in terms of lineal energy can be directly measured by TEPCs. These quality factors are

calculated at the tissue level and are consistent with proposals to double quality factors for fast neutrons. The quality factor values suggested in ICRU Report 40 (ICRU and ICRP 1986) are consistent with relative biological effectiveness (RBE) experiments for low doses of fast neutrons on mammalian cells. Furthermore, it is possible to use this redefinition of quality factors in conjunction with effective dose equivalent methodology to derive fluence-to-effective dose equivalent conversion factors that are about the same value as existing fluence-to-dose equivalent conversion factors. Adoption of this methodology unfortunately will result in greatly increased complexity of calculations.

FIGURE 4.1. Comparison of conversion factors for existing fluence-to-dose equivalent factors and fluence-to-effective dose equivalent factors based on the redefinition of quality factors, Q , as a function of linear energy transfer (LET).

...conversion factors obtained from the Monte Carlo calculations of the range of a neutron in a tissue...
 ...the effective dose equivalent methodology with an anthropomorphic...
 ...as a function of linear energy transfer (LET)...
 ...shown in Figure 4.1...
 ...of energy deposited in a tissue...
 ...for effective dose equivalent...
 ...of dose equivalent at the tissue level is regulated by the...
 ...of effective dose equivalent methodology...
 ...to calculate an effective quality factor...
 ...of dose equivalent, but the authors are hesitant to add yet...
 ...factor to an already complex situation...
 ...quality factors can be redefined in terms of linear...
 ...quality factors are

5.0 OPERATING INSTRUCTIONS FOR THE FIELD SPECTROMETER

Section 5.0 discusses operating instructions for the field spectrometer. This includes a trouble-shooting guide if problems occur. Set-up and operating instructions are contained in procedures 1 through 7 included in Appendix B. Instructions are included for operating both the version of field spectrometer that uses commercial electronics and the version that uses PNL-designed electronic circuitry built into the detectors. Sufficient detail is included for an operator to manipulate the field spectrometer without any other training, but it is recommended that the operator be familiar with the theoretical material presented in Sections 3.0 and 4.0 as well as the material presented in Section 7.0 on construction of the spectrometer. In event of trouble, this background material will aid the operator in diagnosing and solving the problem. The operating instructions are written assuming that the operator has had little experience with computers and that the spectrometer system has been adjusted and thoroughly tested in the laboratory before the operator takes it into the field. The spectrometer system can be adjusted in the field if the operator has some knowledge of the MS-DOS® operating system on the computer, but it is much easier to make final adjustments in the laboratory.

5.1 SET-UP PROCEDURES

This section discusses the logistics involved in making a spectrum measurement in the workplace. Before making any measurements in the field, it is assumed that the spectrometers have been carefully adjusted and checked in the laboratory as described in Section 7.0. Then duplicate detector modules will have the same gain and can be easily exchanged in the field in the event of a malfunction.

5.1.1 Operating Constraints

Before taking measurements, the following operating constraints must be considered. In some facilities, the possibility of contaminating

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spectrometer components exists. The cables connecting the detectors to the analysis module are often routed under glove boxes and have the highest probability for contamination. Routine procedures at PNL require that the cables be sheathed in 2-in.-wide polyethylene sleeves. The plastic sheathing can easily be pulled off the cables if radioactive contamination is found. It also keeps the equipment free of dirt and dust. Airborne contamination may also be a problem, though an infrequent one. Open-pore foam filters can be placed over the air inlets on the right-hand side of the spectrometer case. Often, radon daughters are found deposited on filters, and it is difficult to differentiate between alpha contamination from plutonium and from radon daughters. A disposable filter offers protection for these valuable components.

An important consideration in planning and scheduling a set of measurements is the selection of measurement locations. Coordinating the measurement schedule with operations personnel is mandatory. Health physicists usually want to make measurements in front of glove ports and other locations where personnel are exposed, but this often conflicts with routine operations and production schedules.

The detector modules are separate from the larger analysis module. The detectors can be mounted on small, sturdy tripods and positioned so that they do not interfere with normal working procedures. The detector modules are supplied with holes tapped for 1/4-20 threads for mounting on tripods. Often cables are routed under the glove boxes or securely taped out of the way to eliminate tripping hazards.

To obtain the best statistical accuracy, it is desirable to collect enough data to measure at least 20 mrem. Data can be obtained with exposures to only a few mrem, but the accuracy is decreased. This may require overnight exposures in low dose rate areas.

5.1.2 Laboratory Testing

Before actually beginning the measurements in a radiation area, it is advisable to assemble all of the components to make certain that all pieces are available. Figure 5.1 shows the components required for the prototype PNL field spectrometer. This includes the following:

FIGURE 5.1. The PNL Prototype Field Neutron Spectrometer Developed by PNL with Analysis Module in the Center, TEPC Detector on the Left, and ^3He Detector on the Right

1. the analysis module in the suitcase (with the lap-top computer and its power supply and power cords)
2. the ^3He detector module (the proportional counter, support stand with built-in electronics and a SHV coaxial cable to connect the cable to the support stand) and the TEPC detector module with built-in electronics
3. the power cables and BNC signal cables to connect the detector and analysis modules.

Using a neutron check source, such as ^{252}Cf , is a convenient method to ensure that the unit is functioning properly.

5.1.3 Instructions for Data Analysis in the Lab

With the spectrometer setup in the laboratory, collecting and analyzing data with a calibrated neutron source is a good method of verifying the accuracy of the spectrometer before it is used in the field. Procedures 2 through 7, contained in Appendix B, outline the step-by-step procedures for data collection and analysis. Make certain that the ^3He counter has a slow neutron peak near the first tick mark on the graph of the raw data as described in Procedure 4 in Appendix B. Also, make certain that the value for IGUESS is set correctly in the data file WIRE.DAT by running a TEPC analysis as described in Procedure 5 also in Appendix B.

After collecting data for about 30 minutes, the graph of the raw data should be studied to determine whether a sharp proton edge can be found. The proton edge is close to the channel number corresponding to the half-height of the sharp discontinuity in the graph of the raw data. If a definite proton edge can be identified by the user but the spectrometer's analysis program gives a warning that the data "looks strange for a TEPC spectrum," then the value for IGUESS in the data file WIRE.DAT is probably incorrect. The user can type the command "TYPE WIRE.DAT" to examine the contents of the file. The second line in this file contains the value of IGUESS. This number should be close to the channel number corresponding to the observed proton edge on the raw data graph. If the difference between the proton edge and IGUESS is more than 50, IGUESS must be adjusted. A text editor or work processor can be used to make this adjustment.

5.2 INSTRUCTIONS FOR USING SPECTROMETER IN THE FIELD

Detailed procedures for operating the spectrometer in the field have been included for operators who have little experience in operating electronic edquipment or personal computers; they are not intended to be used by operators who are already familiar with spectrometric measurements. The procedures for setting-up and operating the spectrometer system and reviewing the data as outlined below are included in Appendix B:

- Procedure 1 - Setting up the field spectrometer
- Procedure 2 - Operating the computer
- Procedure 3 - Starting data collection
- Procedure 4 - Starting data acquisition by the ^3He detector
- Procedure 5 - Starting data acquisition by the TEPC
- Procedure 6 - Stopping data acquisition and storing data
- Procedure 7 - Using WordPerfect®

These procedures were developed for the prototype PNL field spectrometer. Some modifications to them may be necessary if the spectrometer system uses commercially available components for the detector modules, as discussed in Section 7.4.1.

5.3 DATA FILES

The time the measurement was made, the analyzed results, and the raw data from each measurement are automatically stored in data files each time an even function button is pressed. These files start with the letters PORT. The program automatically assigns the correct port number to each data file and adds letters in alphabetical order to differentiate among the various measurements. For example, the third measurement from port 4 is stored in the data file named PORT4B.DAT, where the 4 refers to the port number and the letter "B" is the third measurement in the sequence PORT4.DAT, PORT4A.DAT, and PORT4B.DAT.

Once the program is terminated and control is returned to the MS-DOS operating system, a directory of the files may be obtained by typing the command

```
dir port*.*
```

then pressing the return key. This produces a list of data files as shown in the following example:

PORT1	DAT	19379	1-19-88	11:17p
PORT3	DAT	19379	1-20-88	1:13a

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See Appendix A for additional information.

The first column is the name of the file, the second column is the type of extension (.DAT), the third column is the file length, the forth column is the date the file was generated, and the fifth column is the time the file was generated.

It is a good idea to back-up data files to prevent inadvertent loss of data. Remember to format a new, unused disk before attempting to copy data it. To make back-up copies of the data files, the following MS-DOS command can be used to copy from hard disk C in the computer to floppy disk A in an attached floppy disk drive:

copy port*.* a:

Files can also be transmitted to other computers using a terminal emulator program. Specific instructions can be found in the software manual. If the WordPerfect® software has been installed in the personal computer, Procedure 7 in Appendix B may be used to examine the data files.

5.4 TROUBLE-SHOOTING GUIDE

Section 5.4 deals with problems that may occur and methods for handling them. Some simple precautions to avoid trouble are included. Perhaps the most serious problem is damage to the disk drive which may occur when the computer is turned off during a read or write on the hard disk in the computer. This can be avoided simply by waiting 5 seconds for the head to "park" before turning the computer off.

A second problem that can easily be avoided is to remember to disconnect the power to the ^3He detector electronics and wait a few seconds before disconnecting the SHV connectors to the ^3He proportional counter. Therefore, the input transistor won't be harmed. A red LED warning light is mounted on the ^3He detector electronics to warn the operator that power is applied.

Also, at the end of a measurement, turn the computer off. This computer is battery powered and will continue to function for some time after the external power is removed. You can close the cover on the display, and the computer will continue to operate.

As suggested in Section 5.1, the best way to avoid trouble is to set the spectrometer up in the laboratory and test it before taking it out into the field. The gas gain in some TEPC detectors deteriorates with time as contaminants slowly diffuse out of the tissue equivalent plastic walls and reduce the gas multiplication. If the counter has been sitting idle for several weeks, the gain shift may be so severe that the value for IGUESS (i.e., the value for the rough guess for the proton edge channel number) in the data file WIRE.DAT may be incorrect. Testing in the laboratory will demonstrate whether this is the case. The method to adjust the value for IGUESS is given in Section 7.4.7 on construction and adjustment of the TEPC detectors. Changing gas gain is not a problem for most of the new counters with plastic that has been specially treated. Most of these counters show only a 15% gain change in a one-year period.

The operator should be aware that the gas gain can change with temperature. The tissue equivalent gas contains carbon dioxide, which is soluble in the tissue equivalent plastic. As the temperature changes, the solubility changes, thus affecting the gas gain in the detector. Because most workplaces are maintained at nearly constant temperatures, this is not a significant problem. Occasionally, however, measurements are made outside where significant changes in temperature occur. In this case, it may be necessary to change the value for IGUESS using the procedures outlined in Procedure Step 5.5 in Section 5.3.

Table 5.1 is a brief trouble-shooting guide that lists the symptoms, the cause of the problems, and suggested remedies. This guide should make problem solving in the field much simpler.

TABLE 5.1. Trouble-Shooting Guide for Correcting Problems
with the PNL Field Neutron Spectrometer

Symptom	Cause	Remedy
Computer won't turn on	Defective battery or power supply	1) Replace battery or 2) Replace power supply
Program won't start	Autoexec program not installed in computer	See set up procedures for computer installation
Program won't start data collection	1) Cable to MCA not connected or defective	1) Connect ribbon cable to serial port at back of computer
	2) No power to MCA	2) Turn on switch on suitcase
	3) Cables not connected to detectors	3) Check connections and LED on detector modules
	4) defective detector	4) Replace detector module
No data collected by He-3 detector	FET destroyed by disconnecting tube with power applied	Replace the detector module
Double peak in raw data for He-3	Pulse pile-up from slow neutrons	Place boron cover over proportional counter
Excessive count rate at low energies in counter	Excessive gamma exposure rate	Remember to place lead shield over He-3 proportional counter
Program continuously displays warning for TEPC analysis	1) TEPC plugged into wrong port	1) TEPC must be connected to port 3 or 4
	2) Gain shift	2) Examine raw data and estimate new value to insert for IGUESS in data file WIRE.DAT
Program stops during He-3 analysis	He-3 in wrong port	He-3 detector must be connected to port 1 or 2
Program returns to MS-DOS	Power transient stops computer	Start measurement over or use power line conditioner

6.0 TESTING THE FIELD SPECTROMETER SYSTEM

This section describes a series of tests used to verify the accuracy of the neutron field spectrometry system and to verify that it could operate under the rigors of field situations. Section 6.1 describes laboratory tests with calibrated neutron sources to verify the accuracy of the spectrometer measurements; Section 6.2 describes the results of field tests in plutonium facilities. To avoid potential publication delays resulting from classification problems, Section 6.2 does not provide actual spectra and dose rates but does provide a comparison among the prototype field spectrometer and other spectrometers used at PNL. Details of the spectra in the plutonium facilities will be published separately.

6.1 LABORATORY TESTING OF THE FIELD SPECTROMETER

Two different versions of the field spectrometer were subjected to accuracy verification tests in the laboratory. Both versions used the "suitcase" analysis module shown in Figure 5.1 and described in Section 7.3. One alternative used the PNL-developed electronic circuitry described in Section 7.4.2; the other alternative used the commercially available NIMbin modular electronics described in Section 7.4.1. Both versions gave nearly identical satisfactory results.

The first series of tests was performed with a 5-in.-dia spherical TEPC(a) filled with 11.3 torr of methane based tissue equivalent gas and operated at an equivalent diameter of 2 μ m. This counter uses Shonka A-150 tissue equivalent plastic that has been processed to remove impurities that may cause gain shift problems. The spherical TEPC was exposed at 100-cm-centerline distance from a small ^{252}Cf calibration source about 24 hours after the counter was filled. (Experience has shown that counters may experience as much as a 10% gain shift immediately after the counter is filled; this effect seems to disappear after one day.)

Data collected by the field spectrometer were analyzed using the program used in the field spectrometer (listed in Appendix A) and using a laboratory

(a) See Appendix A for additional information.

analysis code "tepc_ng" written at PNL for a HP9000 computer. The results given in Table 6.1 show that the two methods of analysis give almost identical results. In 1984, the dose equivalent rate from the ^{252}Cf source was determined with an estimated uncertainty of 8% to 10% by measurements comparing it to an NBS calibrated ^{252}Cf neutron source. It is assumed that all of the neutron dose originates from the ^{252}Cf isotope, which decays with a half-life of 2.645 years. The dose rate has been adjusted for decay. Some uncertainty in the assumed dose equivalent rate exists because other californium isotopes with different half lives may contribute to the neutron dose rate. In any case, there is remarkable agreement between the values estimated by the TEPC measurements and the assumed correct value. This agreement may be fortuitous in view of the uncertainty in the assumed "correct" value for the dose equivalent rate.

The results given in Table 6.1 represent data taken with the TEPC that has the best resolution available in our laboratory. Measurements were also made with two other TEPCs that are at least 15 years old and do not contain tissue equivalent plastic treated to minimize off gassing of volatile components. These TEPCs exhibit a 25% reduction in gain over a two-week period and have poor resolution, as evidenced by the lack of a sharp proton edge.

TABLE 6.1. Comparison of TEPC Data Analyzed by the Field Spectrometer Code and by a Laboratory Analysis Code

<u>Analysis Code</u>	<u>Average Energy, MeV</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate, mrem/h</u>
Field spectrometer	3.06	10.1	58.0 (6.4% high)
Laboratory analysis	2.3	10.1	55.7 (2.2% high)
Assumed correct quantities	2.3	9.7	54.5

Using these counters, the spectrometer analysis code gave results that varied from 20% too low to 20% too high for the calculated dose equivalent rate. The apparent error in the analysis became worse with time as the resolution of the counter deteriorated. Also, these counters exhibited significant gain changes within the first few hours after being refilled with methane-based tissue equivalent gas. For data collected over several hours, the gain appeared to be reduced. The code picked a proton edge that was too low; this resulted in a number of events with high lineal energy values that overestimated the average quality factor and dose equivalent.

In addition, with the poor resolution counters, an incorrect proton edge value was determined by the spectrometer analysis code. With very little data, a high degree of Fourier smoothing (Aubanen and Oldham 1985) was applied to the data, and the proton edge appears to be adequately determined. With a lot of data (corresponding to exposures of more than 100 mrem), the spectrometer analysis program appears to be over-smoothing the data, which results in the program choosing a value for the proton edge that is several percent too low. This results in an energy calibration value that is too low and consequently the computer code overestimates both the quality factor and dose equivalent values.

These results point out the necessity for performing a series of exposures over several weeks with a constant neutron dose rate to assure that the TEPCs do not deteriorate with time. Even some of the newer TEPCs may exhibit serious gain shift problems, and it is best to determine their operating lifetimes before making measurements in the field.

Measurements were also made with a ^3He proportional counter exposed to a ^{252}Cf neutron source. Because of concerns about high-pressure tubes being transported under hazardous materials shipping regulations, a tube containing less than 40 psia(a) was selected for these measurements. This tube contained 34 psia argon and 5 psia ^3He in a 2-1/2-in.-dia by 12-in.-long cylinder. The response function (i.e., the fraction of counts of a given energy deposition) for this tube is shown in Figure 3.5. As seen in the figure, for neutrons with 5 MeV incident energy, only about 2% or 3% of the

(a) pounds per square inch absolute

events result in a full energy deposition event in the counter. The remainder of the events are either ^3He recoil events or wall events that do not deposit all of the energy of the neutron in the sensitive volume of the counter. In retrospect, this may not have been the best choice for making measurements of higher-energy neutrons (above 3 MeV), but it eliminated the time-consuming paperwork associated with hazardous material shipments between DOE facilities. In some instances, these paperwork requirements can delay measurements by 1 or 2 days.

The results of the ^3He spectrometer measurements are displayed in Table 6.2. Again, the results are in surprisingly good agreement with calculated values. Although there may be some uncertainty with the differential values, the average values for quality factors and dose equivalent rate are close to the accepted correct values. This is, in part, an artifact of the spectral unfolding process and the response function. Neutrons with energies above 5 MeV will interact to produce ^3He recoils or wall events. For these neutron events, the unfolding algorithm used in the analysis code assumes that the energy deposited is the energy of the neutron minus the Q value of the reaction. Because the fluence-to-dose equivalent factors and quality factors are relatively constant with the energy in this energy region, the average quality factors and dose equivalent values are nearly correct. A plot of the fluence as a function of energy has roughly the shape of the spontaneous fission spectrum, but the unfolding algorithm produces an artifact of too many neutrons in the energy range of 200 to 500 keV. Thus, the average neutron energy tends to be low, as shown in Table 6.2. This is not a problem for this gas filling for neutrons with energies below about 3 MeV.

An important consideration in making measurements in the field is how long the spectrometer must be exposed to neutrons before an accurate measurement is achieved. An idea of the sensitivity of the spectrometer can be obtained from the data presented in Table 6.3. Here the detectors have been exposed under identical conditions from the ^{252}Cf source for various times. Surprising accuracy for the average values for quality factor and dose equivalent rates can be achieved in only a few minutes. However, the differential neutron energy spectra are quite different for short and long

TABLE 6.2. The ^3He Spectrometer Exposed to a Calibrated ^{252}Cf Neutron Source

	Energy Range, MeV	Average Energy, MeV	Average Quality Factor	Dose Equivalent Rate, mrem/h
Spectrometer measurement	0-5	1.72	9.6	201 (7.8% low)
Assumed correct values	0-5	1.7	9.8	218
	0-20	2.3	9.7	

TABLE 6.3. Variations in the Spectrometer Results as a Function of the Exposure Time or Accumulated Dose

Time	TEPC			^3He		
	Average Energy, MeV	Quality Factor	Dose Equivalent Rate, mrem/h	Average Energy, MeV	Quality Factor	Dose Equivalent Rate, mrem/h
30 sec	2.43	10.6	60.7	1.82	9.4	207
30 min	3.22	10.0	57.2	1.76	9.5	202
1 hr	3.21	10.0	57.5	1.74	9.5	202
2.5 hr	3.06	10.1	58.0	1.73	9.5	201
Assumed correct value	2.35	10	54.5	2.35	10	218

exposures. An exposure of at least 20 mrem to 100 mrem is required for reasonably accurate differential spectra for the absorbed dose distribution as a function of lineal energy measured by the TEPC or the neutron flux density as a function of incident neutron energy as measured by the ^3He detector. In Table 6.3, the assumed correct value for the dose equivalent rate is 218 mrem/h for the ^3He detector and 54.5 mrem/h for the TEPC.

6.2 FIELD TESTING THE FIELD SPECTROMETER SYSTEM

During late summer and fall of 1987, the field spectrometer system was taken to several field locations at two DOE sites for operation under realistic conditions. Field locations at the Fast Flux Test Facility (FFTF)

Fuel Assembly Building (308) at Hanford and the Plutonium Processing Building (TA-55) at Los Alamos National Laboratory (LANL) were chosen for the field tests because these work locations represent typical DOE laboratory locations where personnel are exposed to neutrons. Additional tests were conducted in the radiation calibration laboratories at both Hanford and Los Alamos. Details of these measurements will be included in a future report.

In most cases, the neutron spectra encountered in these field tests were produced by spontaneous fission of plutonium and californium isotopes. In these field situations, the spectra were moderated and scattered by structural and hydrogenous materials near the various neutron emitters. A fraction of the neutron spectra resulted from (α, n) reactions with low atomic number nuclei in the source materials.

The neutron dose equivalent rates encountered at the work locations were generally quite low, with readings from 0.1 mrem/h to 60 mrem/h depending on the source magnitude and shielding used to reduce the neutron exposures. The highest dose equivalent rates were found in plutonium storage vaults. Because of the low dose equivalent rates, relatively long counting times were required for the spectrometer system to acquire the required number of counts (events) for the specified statistical certainties.

The field measurements were coordinated with the operational staff and the health physics staff at both DOE sites to obtain the most meaningful data while minimizing the impact on routine operations. In many cases, long counting times were needed, and the spectrometer system was set up for overnight operation of all four detectors.

The spectrometer system was operated with ^3He spectrometers and tissue equivalent proportional counters. Measurements were also conducted simultaneously with an independent spectrometer system using additional ^3He spectrometers and tissue equivalent proportional counters. In some instances, a multisphere spectrometer was used to verify proper operation of the PNL field spectrometer. Spectra and dose equivalent rates obtained by both systems were essentially identical.

In general, all equipment operated properly. Calibration checks were conducted to provide energy scale determination and accuracy of dose equivalent measurements. During the measurements, however, several problems were

encountered. As a result, some procedural and hardware modifications were initiated, as outlined in the following paragraphs.

During measurements, the PNL spectrometer is programmed to operate until the data accumulated satisfies the statistical accuracy needed. In low dose rate fields, several hours may be required to accumulate enough data to meet these requirements. Power interruptions occurred at the Hanford and Los Alamos work locations. If power line problems occur, the microprocessor in the spectrometer may malfunction. In fact, it did malfunction once at Los Alamos.

Because of extensive shielding on glove boxes, the dose rates were very low, and long data collection times were required to obtain sufficient data to use the proton edge for energy calibration. A built-in alpha source for calibration would be a great improvement when results are needed in a short time. However, including the alpha source necessitates following the requirements for radioactive shipments, thus limiting the convenience of using the spectrometer.

The ^3He spectrometer requires a proportional counter with greater stopping power to count high-energy neutrons (energies above 3 MeV) more efficiently. The present tube is limited to 40 psi to avoid hazardous materials shipment requirements. In December of 1987, a manufacturer obtained an exemption from the U.S. Department of Transportation. These higher pressure tubes have been procured from the manufacturer and will be incorporated in a the spectrometer.

In conclusion, the field tests demonstrated that the prototype spectrometer will function under the rigors of the workplace. The modification suggested by field testing should allow the spectrometer function better in low dose rates.

7.0 SPECTROMETER CONSTRUCTION

Section 7.0 presents details for the construction of the field spectrometer. A modular approach was used, so that any defective component could be quickly replaced for easy repair in the field. For wide-spread applications, commercially available components were used whenever possible. Construction plans are given for two versions, one using only commercially available components and the other using electronic circuitry developed at PNL. Section 7.2 describes the version constructed entirely of commercially available components. Sufficient information is provided so that a health physicist could assemble a working spectrometer from components without knowledge of electronic construction techniques. The first PNL prototype spectrometer used a commercially available MCA mounted in an aluminum suitcase, as described in Section 7.3. Section 7.4 describes the details for the construction of the detector electronics and the adjustments that must be made to operate the electronics properly. Sections 7.3 and 7.4 assume that the persons performing the work are skilled electronics technicians or are familiar with printed circuit board assembly techniques and a knowledge of electronics. Finally, Section 7.5 gives cost estimates for the various components and alternatives.

Because of the size of the computer code, a separate document containing and describing the code will be issued shortly. The code will be made available through a code distribution center, such as Radiation Shielding Information Center (RSIC).

7.1 COMPONENT SELECTION

This section contains information relevant to all of the various alternate designs for the field neutron spectrometer. Section 7.1.1 describes the selection of an appropriate computer and MCA, and Section 7.1.2 discusses the selection of detectors.

7.1.1 Selection of Electronic Modules

Many different minicomputers are available and are powerful enough to handle the necessary spectrum unfolding codes. For maximum versatility, an IBM PC® compatible computer was selected, so that the software developed can

be used in any of the IBM PC® clones that are widely used in DOE facilities. A GRiDcase®(a) lap-top computer was selected for the PNL prototype, although there are several other IBM PC® clones available for this application. Although several other IBM PC® clones are applicable, the GRiDcase® lap-top computer was selected for the first prototype, because it was available at PNL when the project was started. The GRiDcase® 3 computer is smaller and more compact than the standard IBM PC®. It is 15 in. deep, 11-1/2 in. wide, 2 in. high, and weighs about 12 lb. The model selected has a built-in 10-Mbyte hard disk to store the analysis programs and hundreds of measured spectra. A gas plasma display is provided for ease of viewing in sunlight or complete darkness. An alternate back-lit liquid crystal display (LCD) can also be used. The MS-DOS® operating system is resident in read only memory (ROM), so that the user does not have to be familiar with computers to actuate the analysis system. It can be used in almost any of the harsh operating environmental condition found at DOE facilities. Also, the user is cautioned that several less expensive computers may not perform under adverse operating conditions, although they are certainly suitable for normal laboratory conditions.

Several different portable MCAs can be used for recording spectrometric data. A number of analog-to-digital converter (ADC) or MCA cards are also available that can be fitted into an IBM PC® computer or expansion box. However, most of these cards interface directly with the computer bus. The computer can only be used for collecting data while the MCA is in use, because the MCA directly accesses the computer memory, thus precluding the use of the computer for other calculations. These cards are not compatible with the GRiDcase® computer (they are too large to fit inside of one), but they will fit into an expansion box. Several stand-alone MCAs are compatible with the GRiDcase® computer, including the Ortec ADCAM(a) units and the Nuclear Data MicroMCA.(a) Both of these units are designed to fit into NIMbin hardware that is widely available at most DOE facilities. The Ortec ADCAM unit was selected because there was one available at PNL when the project was initiated. The ADCAM unit uses a separate Z80 microprocessor to store the MCA data. Thus, the ADCAM unit can run independently while the

(a) See Appendix A for additional information.

GRiDcase® computer is used to analyze and display the spectral data. The ADCAM unit is controlled using standard ASCII character commands from the computer or a terminal. The PNL prototype uses a version of the Ortec ADCAM that has four inputs so that four measurements can be made simultaneously. This unit can be modified to make 16 measurements with different detectors, if desired.

The analysis module containing the MCA and the computer can be configured in several different ways. One version using only commercially available components is discussed in Section 7.2; an alternate version using PNL-developed circuitry is discussed in Section 7.3.

7.1.2 Selection of Detector

As discussed in Section 2.0, several different types of detectors can be used for field spectrometry. For the PNL prototype, the authors selected ^3He proportional counters and TEPCs.

The first prototype used ^3He proportional counters manufactured by Reuter-Stokes(a) which were already in use at PNL for nuclear reactor measurements. These counters contained 5 psia(b) of ^3He , 34 psia of argon, and a small amount of carbon dioxide in a 2-1/2-in.-dia, 12-in.-long cylindrical counter. The counters were fitted with a female SHV connector in place of the type HN connector usually supplied by the manufacturer. A number of manufacturers supply proportional counters filled with ^3He , including Reuter-Stokes, Harshaw Chemical Co.,(a) and others.

The pressure in these counters was limited to less than 40 psia, because any pressurized container with more than 40 psia pressure constitutes a hazardous material as defined by the U.S. Department of Transportation (DOT). In DOE facilities, special precautions must be taken to handle hazardous materials, and formal procedures must be followed. Vehicles carrying hazardous materials such as compressed gases must exhibit specific warning placards. Hazardous materials cannot be shipped aboard passenger carrying aircraft. For practical reasons, the proportional counter used in the prototype contained less than 40 psia to avoid these restrictions. These

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- (a) See Appendix A for additional information.
(b) pounds per square inch absolute pressure

tubes are useful for neutron energies below about 3 MeV, but they are not sensitive enough at higher energies. The majority of interactions in the counter produce charged particles that strike the walls for neutron energies above about 2 to 3 MeV for tubes with pressures below 40 psia. The obvious solution for measurements at higher energies is to use tubes with higher gas pressures. In December of 1987, Reuter-Stokes obtained an exemption from the DOT to allow higher pressure tubes (above 40 psia) to be exempt from these restrictions if shipped in special containers.

The second type of neutron detector used in the PNL prototype is the TEPC. These detectors are available as spherical or cylindrical proportional counters. The usual form used for spectrometric measurements is a spherical counter of tissue equivalent plastic with 1/8-in.-thick walls. The sensitivity of the counter depends on the surface area of the plastic walls, where most of the charged particle secondaries originate. Because many work locations have low neutron dose rates, a 5-in.-dia spherical detector with a single wire was selected for the prototype spectrometer. An alternate form of counter, called the Rossi counter, uses a helical grid operated at an intermediate voltage to create more uniform electric fields near the anode to give more uniform gas gains. The Rossi counter, however, is more susceptible to damage if dropped and to the generation of spurious signals if subjected to vibration.

The TEPC is available with a built-in ^{244}Cm alpha calibration source. These sources can be used for the energy calibration, i.e., the correlation between the pulse height and the energy deposition in the counter. The sources are small enough to be exempt from NRC licensing requirements, so the counters with alpha sources are commercially available.^(a) However, at many DOE facilities even small transuranic sources are inventoried. Movement of the counters between buildings may constitute a radioactive shipment, and formal shipping procedures must be followed. This severely limits the usefulness of detectors with calibration sources. Therefore, no detectors with radioactive sources were used for the PNL prototype spectrometer.

(a) See Appendix A for additional information.

7.2 SPECTROMETER BASED ON COMMERCIAL COMPONENTS

In one version of the spectrometer, all equipment is commercially available NIMbin components, including proportional counter preamplifiers, pulse shaping amplifiers, high voltage power supplies, the ADCAM MCA, and a NIMbin with a power supply that provides 6, 12, and 24 VDC. A block diagram of how these components are connected is given in Figure 7.1. This version is not as portable, but parts are easy to procure and assemble. In this version the detectors and amplifiers are connected by cables to the high voltage power supplies and amplifiers mounted in NIMbins. Signals from the amplifiers are routed to the MCA which consists of a multiplexer/router and a multichannel buffer. The data are stored in the multichannel buffer until it is interrogated by the computer. The computer controls the data acquisition by the multichannel buffer, then transfers the data to the computer memory, analyzes it, and displays the results. A listing of the PNL-developed software will be published in a separate document.

Many commercially available electronic components suitable for mounting in the NIMbin shown in Figure 7.1 are available. For the sake of

FIGURE 7.1. Block Diagram of Spectrometer Using Only Commercially Available Components

illustration, a description of the components and equipment settings using Ortec^(a) NIMbin equipment is shown in Table 7.1. A more complete description of the necessary detectors is given in Section 7.4, and a list of sources of supply is given in Appendix A.

7.3 CONSTRUCTION OF PROTOTYPE ANALYSIS MODULE

The analysis module basically consists of an IBM PC® compatible lap-top computer, a multichannel pulse height analyzer, and the ancillary power supplies. The computer controls the operation of the MCA, analyzes the data collected, and displays the results. The components necessary for constructing the prototype that fits into an aluminum suitcase are listed in Table 7.2. Other equally suitable components are available; these components were selected because they were available in our laboratory.

To complete the prototype analysis module, it was necessary to fabricate the special mounting brackets shown in Figure 7.2 and the special heat sink fabricated from a finned aluminum extrusion as shown in Figure 7.3. These brackets were fabricated by a PNL shop, but they can be fabricated by almost any machine shop from aluminum stock. The mounting brackets are used to hold the multichannel buffer and multiplexer in position as shown in Figure 7.4. The components are fastened to a 1/8 in. thick aluminum plate, approximately 23-3/8 in. long by 17-1/2 in. wide, that fits inside the suitcase. The aluminum plate is held in position by attaching it to mounting brackets provided by the manufacturer of the aluminum suitcase.

It is suggested that all pieces shown in Figures 7.2 and 7.3 be fabricated first, then assembled on the mounting plant shown in Figure 7.4. The aluminum mounting plate should fit easily into the suitcase with only a small gap between the plate and the suitcase. This may involve custom fitting if the suitcase frame is bowed. Drill the air vents (the 1-in.-dia holes), along with the holes for the D connectors, power outlet, switch and power cord at the locations shown in Figure 7.4. Then mount the multiplexer, muffin fans, and multichannel buffer at the locations indicated. The muffin fans are held in position by the mounting brackets "A" in Figure 7.2 which

(a) See Appendix A for additional information.

TABLE 7.1. Example of Components Required for Construction of Field Neutron Spectrometer(a)

<u>Component</u>	<u>Settings</u>
Preamplifier, Ortec 142 PC (1 required for each detector)	SHV cable from HV connector to HV power supply BNC cable from BNC marked "Energy" to amplifier Preamp power cable to amplifier
Amplifier, Ortec Model 571	Preamp power cable to connector on rear of amplifier Signal cable from preamp to BNC connector marked IN on rear BNC signal cable from UNI output on amplifier to INPUT on mixer/router Time constant: 2 μ sec Output: positive Coarse gain: adjust as necessary Fine gain: adjust as necessary
High Voltage Power Supply, Ortec Model 456	Polarity: positive, unipolar Voltage: 1300-1800 V for ^3He 600 V for TEPC SHV cable connected to preamp
Multiplexer with 4 Inputs, Ortec Model 476-4	Ribbon cable from multichannel buffer BNC signal cables from amplifier outputs
Multichannel Buffer, Ortec 918A	Ribbon cable to connector on rear of multiplexer/router (See Section 7.3, Tables 7.6 and 7.7 for internal switch settings and cables to computer)
NIMbin and Power Supply with 6, 12, and 24 V, Ortec Model 401	None

(a) See Appendix A for additional information.

TABLE 7.2. Components Required for Construction of a Prototype Analysis Module(a)

<u>Quantity</u>	<u>Component</u>	<u>Manufacturer</u>
1	Multichannel Buffer	Ortec ADCAM Model 918A
1	Multiplexer with 4 Inputs	Ortec Model 476-4
1	Portanim with 6, 12, and 24 V	Berkeley Nucleonics Model AP-3
1	Aluminum Suitcase, 18 in. x 24 in. x 7 in.	Zero Halliburton
4	Cooling Fans	Microboxer Model 2412PS-12W-830
4	Bulkhead BNC Connectors, Female	
2	Connector for NIMbin Power	Amphenol AMP202516-3
8	D Connector, 9 Pin, Female	Amphenol 17-10090-1
8	D Connector, 9 Pin, Male	Amphenol 17-20090-1
3	D Connector, 25 Pin, Female	Amphenol 17-10250-1
1	D Connector, 25 Pin, Male	Amphenol 17-20250-1
1	Outlet Socket, 120 V, with Ground	
1	Illuminated Power Switch	
1	Power Cord for 120 V	
1	Socket for Power Cord	

(a) See Appendix A for additional information.

FIGURE 7.2. Plans for Fabrication of the Mounting Brackets Used in the PNL Prototype Spectrometer

FIGURE 7.3. Plans for Fabrication of the Heat Sink Used in the PNL Prototype Spectrometer

FIGURE 7.4. Diagram for the Placement of Components on the Aluminum Mounting Plate Used in the Prototype PNL Spectrometer

also fit over the flange on the NIMbin components to secure them in place. It is a good idea to fasten one mounting bracket at a time, using flat head 8-32 machine screws. There will invariably be some misalignment if all the holes for the mounting brackets are drilled at one time.

After the NIMbin components have been mounted, position the finned aluminum heat sink in position and mount with flat head machine screws. When everything is installed correctly, air is pulled through the air inlet holes on the right side, pulled through the multiplexer, and then passed through the 4 muffin fans. Cooling air is then forced through the multichannel buffer and into the finned heat sink, then exits through the air vent holes on the left side.

Because of time constraints for completing this project, the NIMbin power supply was removed from a Berkeley Nucleonics Corp. Model AP-3 NIMbin. Many other suitable power supplies are commercially available. The AP-3 model has the 6-V supply necessary to operate the multichannel buffer. The power supply board was sawed into two pieces, with care taken not to saw through the printed circuits. The power supply board was then mounted on 1-in.-high hexagonal stand-offs fastened to the aluminum mounting plate. The voltage regulators were mounted on the finned aluminum heat sink at the positions shown in Figure 7.3. All the wiring is color coded, but it is a good idea to make notes and replace one regulator at a time. The power transformer is mounted at the approximate position shown in Figure 7.4.

Although not shown on the figure, it may be a good idea to drill extra air holes for dissipating heat from the transformer, because there is no forced convection to cool it. Mount a terminal strip at the position shown. Place a sheet of aluminum or plastic veneer over the mounting plate to hide the screw heads, place expanded metal grills over the air vents, and the mechanical layout is completed. Remember to leave holes for the air vents. The computer and its power supply are held in place on top of the mounting plate using hook and loop fasteners.

The electrical wiring required for the prototype spectrometer is relatively straightforward. Use the terminal strip to route 120 VAC to the muffin fans, and wire the power-supply board directly to the electrical switch. The electrical outlet is wired in parallel so that power is

available to the computer whenever the unit has power applied through the cord receptacle. If the wiring has not been damaged during disassembly, it is possible to use the NIMbin connectors directly from the AP-3 Portanim. These can also be connected to the terminal strip if desired. The NIMbin power connectors are wired according to the pin-out conventions adopted by DOE as shown in Table 7.3. Perhaps the most difficult part of the electrical wiring is wiring the D connectors that provide power to the preamp/amplifier circuits and connect the ADCAM unit to the computer. These are wired according to the pin-out convention listed in Table 7.4. The cable from the back of the multichannel buffer to the D connector link to the computer is wired according to Table 7.5.

To avoid sharp bends in coaxial signal cables, four additional BNC female bulkhead connectors were placed in the rear panel of the Ortec Model 476A multiplexer. Coaxial signal cables were then routed from the multiplexer to the bulkhead BNC connectors positioned near the 15 pin D connectors. These connectors provide 12-V power to the detector electronics and accept the signal back from the detectors. The cable connections between the multiplexer unit and the multichannel buffer are shown in Table 7.6.

TABLE 7.3. Bin/Module Connector Pin Assignments for Atomic Energy Commission (AEC) Standard Nuclear Instrument Modules per TID-20893 (Rev. 4)

<u>Pin</u>	<u>Function</u>	<u>Pin</u>	<u>Function</u>
10	+6 volts	33	117 volts ac (hot)
11	-6 volts	34	power return ground
16	+12 volts	41	117 volts ac (neutral)
17	-12 volts	42	high quality ground
28	+24 volts	G	ground guide pins
29	-24 volts		

Note: Pin configurations for Amphenol 202516-3 connector or equivalent

TABLE 7.4. Connector Pin Assignments for Preamplifier/Amplifier Modules

<u>Pin</u>	<u>Function</u>	<u>Pin</u>	<u>Function</u>
1	ground (shield)	6	-24 volts
2	ground	7	+24 volts
4	+12 volts	9	-12 volts

Note: Pin configurations for Amphenol 17-10090-1 connector or equivalent (9 Pin D Connector)

TABLE 7.5. Connector Pin Assignments for Connection Between ADCAM Module and Computer (25 Pin D Connector for RS-232-C Serial Interface)

<u>Female Connector to Computer</u>		<u>Female Connector to Ortec ADCAM</u>
pin 1	connects to	pin 1
pin 2	connects to	pin 3
pin 3	connects to	pin 2
pin 4	connects to	pin 5
pin 5	connects to	pin 20
pin 6	connects to	pin 4
pin 7	connects to	pin 7
pin 8	connects to	pin 4

Note: Pin configurations for Amphenol 17-10250-1 female 25-pin connector. Use these pin connections; the connections listed in the ADCAM manual, Section 4, don't work.

This completes the wiring of the analysis module. Before plugging everything in, it is a good idea to check all the voltages listed on the pin-out diagrams in Tables 7.3, 7.4, and 7.5. A photograph of the completed assembly is shown in Figure 7.5.

TABLE 7.6. Switch Settings and Connections Between the Ortec Model 918A ADCAM Module and the Ortec Model 476-4 Multiplexer

<u>Setting/Connection</u>	<u>918A Module</u>	<u>476-4 Multiplexer</u>
Switch Settings on front	Gate-coincidence	normal multiplex
Cable connection on rear	ribbon cable	connects to control & data bus
	bzot	connects to ADC busy
	ADC in	connects to linear out
	gate	connects to gate out

FIGURE 7.5. The Multiplexer, Multichannel Buffer, and Power Supply Mounted on an Aluminum Plate

Before the multichannel buffer is installed, set the switches to the positions indicated in Table 7.7. If these switches are not set correctly, the computer will not communicate properly with the multichannel buffer. Also, check the manual for the Ortec model 476A multichannel buffer to ensure that the factory has installed the internal jumpers correctly. After everything is installed, leave the unit outside of the aluminum suitcase until it has been demonstrated that the computer communicates properly with the multichannel buffer. Under normal operations, when the unit is first turned on, the computer resets the buffer memory, and the "CPU busy" light is brightly illuminated (see Figure 7.5). When the computer program starts data acquisition, the "ADC busy" light is illuminated. If these lights fail to be illuminated at the proper time, the computer is not communicating properly. Check all the switch settings, and the internal jumpers, and make certain that all the cables are connected and power is supplied to the computer and both of the ADCAM units. At this point, all the circuitry should be operating properly. The last step is to check the linearity of the Ortec multichannel buffer by using a calibrated pulse generator. Use the procedures outlined in Section 5.0 to acquire pulse height data using the computer control. The instructions for installing the software and a listing of the computer program will be published in a separate report.

TABLE 7.7. Switch Settings in Ortec Model 918A Multichannel Buffer to Enable Communication with IBM PC® Compatible Computer Using the Serial Interface

<u>Position No.</u>	<u>Switch S1</u>	<u>Switch S2</u>	<u>Switch S3</u>
1	on	off	on
2	off	on	on
3	on	on	off
4	on	on	off
5	on	on	off
6	on	on	on
7	on	on	off
8	on	off	on

A plot of pulse height versus channel number in the ADCAM unit should be linear, and a straight line fit of the data points should pass through zero. The unit is usually set correctly at the factory, so this step may not be necessary. If the ADC is not linear through zero, consult the manual supplied with the unit. This should complete the check-out of the electronics. The assembly can then be placed in the aluminum suitcase using the mounting brackets supplied by the suitcase manufacturer.

7.4 DETECTOR MODULES

There are several alternatives for the detector electronics. One option, outlined in Section 7.4.1, is to use only commercially available electronics. Another alternative, discussed in Section 7.4.2, is to construct the printed circuits developed at PNL. The following discussion assumes that the reader is familiar with electronic assembly techniques.

7.4.1 Commercially Available Electronics

The electronic modules required for the various detectors can be constructed entirely from commercially available NIMbin modular components, as shown in Figure 7.6. The figure shows a 5-in.-dia TEPC attached to a preamplifier. The same modular electronics can also be used for the ^3He detectors. All of this equipment is rather bulky but can be easily carried by one person.

As an example of a system using only commercially available electronics, Table 7.8 lists the NIMbin components shown in the Figure 7.7. Shown are Ortec components that were on hand at PNL; other equivalent components are available from other manufacturers, such as Canberra.^(a) In Figure 7.6, an 18-in.-long SHV to SHV coaxial cable connects a 5-in.-dia spherical TEPC to an EG&G Ortec Model 142PC preamplifier. A 15-ft-long coaxial cable connects the SHV connector on the preamplifier to the SHV connector on the rear face of an Ortec Model 459 high voltage power supply. A number of equivalent high voltage power supplies are commercially available that can supply 650 VDC for the TEPC or 1200-2000 VDC for the ^3He proportional counter detectors. A 15-ft-long BNC to BNC coaxial signal cable connects the signal output marked "ENERGY" on the Ortec 142PC preamplifier and the signal input connector

(a) See Appendix A for additional information.

FIGURE 7.6. Commercially Available NIMbin Electronics for the Spectrometer Detectors

marked "IN" on the rear of the EG&G Model 572 amplifier shown in Figure 7.6. Also, the preamplifier is supplied 12 VDC through the cable connected to the 9 pin D connector marked "PREAMPLIFIER" on the rear of the amplifier. The signal to the analysis module, described in Section 7.3, is supplied by a BNC-to-BNC 93-ohm coaxial cable connected to the output connector marked "UNI" on the front face of the amplifier. All of the NIMbin components are mounted in a Berkeley Nucleonics Model AP-2 Portanim.^(a) This system has

(a) See Appendix A for additional information.

TABLE 7.8. Electronic Components Used to Provide Signals from the Spectrometer Detectors(a)

<u>Quantity</u>	<u>Component</u>	<u>Manufacturer</u>
1	NIMbin and power supply	Berkeley Nucleonics Corp. Model AP-2 or AP-3
2	proportional counter preamplifier and cable	EG&G Ortec Model 142PC or equivalent
2	signal amplifier	EG&G Ortec Model 572 or 575A
2	high voltage power supply 0-5000 volts	EG&G Ortec Model 456 or equivalent
1	³ He proportional counter 2-1/2-in. dia filled with 2 atm He & 8 atm Ar	Reuter-Stokes Div. of General Electric Co.
1	tissue equivalent proportional counter	Far West Technology 5-in. single wire counter
4	coaxial signal cables 15-ft-long, 93 Ω , BNC to BNC	Canberra Industries or EG&G Ortec
2	HV coaxial cables 15-ft-long, 93 Ω , SHV to SHV	Canberra Industries or EG&G Ortec

(a) See Appendix A for additional information.

been used for many years at PNL, but other commercially equivalent components may be used.

7.4.2 Construction of Detector Modules

An alternative to the use of commercially available electronics is to use a combination preamplifier, amplifier, and high-voltage power supply built into the base of the detectors. These units were developed at PNL for other applications, but they are ideally suited to this application. This option is potentially less expensive than the commercially available electronics. The entire package, shown in Figure 7.7, is certainly much smaller and easier to use. This section (7.4.2) gives details of how to construct this assembly. Schematic diagrams of the TEPC detector circuitry developed at PNL are presented in Figure 7.8, Figure 7.9, and Figure 7.10.

FIGURE 7.7. The PNL-Developed Preamplifier/Amplifier/
High Voltage Power Supply Mounted in a TEPC

Figure 7.8 shows the details of the preamplifier input circuit. To reduce noise, the input field effect transistor (FET) is mounted on a teflon plastic block or ceramic stand-off insulator near the feed-through of the proportional counter. This is shown in Figure 7.7. The preamplifier input is connected to the shaping amplifier shown in the schematic diagram in Figure 7.9. This amplifier provides gaussian shaped pulses and two stages of gain. Use the output labeled "NEUT" for 0 to 10 volt gaussian positive pulses for the MCA. Finally, the high voltage power supply, shown in Figure 7.10, provides 400 to 650 VDC to power the proportional counter. This power supply is exceptionally stable if constructed properly, because it uses very low temperature coefficient resistors in the HV control circuitry. The

output of the supply varies by less than 1 volt over a 50°C temperature range. Very little energy is required to operate the proportional counters; therefore, small storage capacitors are used. The high voltage supply can provide a perceptible shock, but it is not lethal.

A printed circuit board approximately 5-1/2 inches long and 1-1/2 inches wide is available from Hecox and Associates, a commercial vendor.^(a) The details of the component layout on this board are shown in Figure 7.11. The components labelled B1 and B2 are ferrite toroids with several loops of wire on them used to reduce noise from the power supply travelling back through the 12-V supply. They are not essential for operation and can be eliminated, but the electronic noise may increase substantially. The board is designed with two jumpers, which can be removed to completely isolate the 12-V supply and ground connections between the high voltage power supply and the amplifier. In fact, the board may be sawed into two pieces to separate the high voltage supply from the amplifier. The components labeled R27 to R36 are 100 Mohm low-temperature coefficient resistors. The stability of these resistors determines the stability of the feedback circuit used to regulate the high voltage. Thoroughly clean these components and keep fingerprints, resin and other materials off the precision resistors! The input FET is connected to the pads on the printed circuit board as shown in Figure 7.11. Several different FETs could be used, but a 2N4416 is satisfactory for low noise operation. The output to the analyzer module is taken from the pin marked "NEUTRON" on connector J1 in Figure 7.11. This output is capable of driving a 100-ft-long cable. However, if very low impedance loads are used, it will be necessary to replace U4 with a voltage follower or buffer, providing R24, R25, R26, and C19 are changed as necessary. This modification is being considered for the ³He detector module.

After the boards are constructed, they are mounted inside the housing of 5-in.-dia spherical TEPCs manufactured by Far West Technology.^(a) One simple method of mounting the boards is to slide them into slots machined into plastic rails which are fastened to the proportional counter housing. The TEPCs can be supplied with 15 pin D connectors by the manufacturer. The

(a) See Appendix A for additional information.

7.22

Battelle N.W. Labs

TEPC DETECTOR TUBE PREAMP

SIZE	FILE	REV
B	TEPC8	A
DATE	01-18-88	SHEET 1 OF 1

FIGURE 7.8. Schematic Diagram of Preamplifier Input Used in PNL Detector Electronics

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FIGURE 7.9. Schematic Diagram of Amplifier Used in PNL Detector Electronics

FIGURE 7.10. Schematic Diagram of High Voltage Power Supply (400-650 V)
Used in PNL Detector Electronics

FIGURE 7.11. Layout of Components on Printed Circuit Board Used for PNL Detector Electronics

+12 V, -12 V, and common ground connections are supplied to the printed circuit board using the pin locations specified in Table 7.4.

Although the preamplifier and amplifier circuitry shown in Figures 7.8, 7.9, and 7.11 are adequate for use with the ^3He proportional counter detector, the high voltage power supply must be modified to provide the higher voltages (1200 V to 2200 V) required for the ^3He detector. A schematic diagram of the high voltage power supply is shown in Figure 7.12. This circuit is essentially a pulse generator with a voltage quadrupler. A printed circuit board for this circuit was supplied by a commercial vendor. (a) The ferrite toroids labeled B1 and B2 are not essential to the circuit, but they reduce the electronic noise that can be propagated back through the supply voltage. With a 12-V supply, the high voltage power supply can produce 400 to 2800 V, which is adequate for almost all proportional counters. The output voltage is controlled by a potentiometer labeled R4 in Figure 7.13.

In some working environments, the ^3He proportional counter must be covered by 1) a 1/4-in.-thick lead shield to reduce gamma ray interactions or 2) a boron cover to reduce slow neutron interactions to prevent pulse pile-up. The support for these shields, shown in Figure 7.14, was fabricated from a 2-1/2-in.-wide aluminum channel. This support stand is a convenient location to mount the preamplifier/amplifier electronics (shown in Figures 7.8, 7.9, and 7.11) and the high voltage power supply (shown in Figures 7.12 and 7.13). The printed circuit boards are mounted into slots cut into plastic rails glued to the sides of the aluminum channel. Some care must be taken to drill a hole in the channel over the high voltage adjustment so that the voltage can be changed in the assembly. The input to the preamplifier is supplied by a female SHV connector as shown in Figure 7.14. A short SHV-to-SHV cable connects the assembly to the proportional counter. Also, a light emitting diode with a 3-ohm resistor in series is wired across the 12-V supply to warn the operator that the assembly is energized. This unit can deliver a nasty but non-lethal shock. Also, if the proportional counter is removed while the amplifier is energized, the input FET may be destroyed or damaged.

FIGURE 7.12. Schematic Diagram of High Voltage Power Supply for ^3He Detector

FIGURE 7.13. Layout of Components on Printed Circuit Board for the High Voltage Power Supply for the ^3He Proportional Counter

FIGURE 7.14. PNL-Designed Electronics Shown Mounted Inside the TEPC Detector and Support Stand for the ^3He Detector

7.4.3 Laboratory Adjustments of Detector Electronics

Some adjustments must be made to the electronic modules so that all of the detector modules are interchangeable. Both the amplifier and the high voltage supplies must be adjusted. These adjustments are best performed in the laboratory using a small neutron source. The following procedures outline the methods used to adjust the electronic circuitry.

The test equipment required for these adjustments includes an oscilloscope (for example, a Tektronix(a) Model 485), an electrostatic voltmeter (for example, Sensitive Research Instrument Company(a) 0-1 kV for the TEPC or 0-3 kV for the ^3He detector), a power supply (for example, Power Designs Inc.(a) Model TP340), a pulse generator (for example, an Ortec Model 480(a)) or a small neutron source, and an MCA (for example, a Canberra Series 40 MCA(a)).

7.4.3.1 Procedure for High Voltage Adjustment

To adjust the high voltage power supply for the TEPC, refer to Figure 7.11 for location of components. Then follow these instructions: first attach a lead from the high voltage side of the electrostatic voltmeter to resistor R3. Connect the ground side of the electrostatic voltmeter to a convenient ground such as the ground pin on the supply connector. Connect the +12 V, -12 V, and common leads from the low voltage power supply to the power connector on the board. Turn on the power supply.

Set potentiometer P3 (R44) to full resistance by turning clockwise to the end of the adjustment range. Place an oscilloscope probe on pin 10 of U7 (CD4098 integrated circuit). Adjust potentiometer P2 (R45) to give a pulse width of about 100 μsec . Adjust potentiometer P1 (R46) to change the repetition rate of the pulses.

Starting full clockwise, turn the potentiometer counterclockwise until the maximum voltage is achieved. (It may be a good idea to remove the lead to the anode of the proportional counter to avoid damaging the counter.) Now adjust P3 (R44) counterclockwise to the desired voltage, which should be about +600 VDC for most single wire proportional counters. NOTE: the high voltage power supply will not provide enough current to drive the "Rossi" counters with a voltage divider network, unless the values of the resistors in the voltage divider are increased.

The high voltage supply for the ^3He proportional counter is much easier to adjust. Refer to Figures 7.12 and 7.13 for the location of the components. Attach the electrostatic voltmeter to the output of the power

(a) See Appendix A for additional information.

supply and to a convenient ground. Attach the +12 V, -12 V, and ground leads to the connector on the printed circuit board. Turn on the power supply. Then adjust the high voltage to the value recommended by the manufacturer of the proportional counter by adjusting potentiometer R4. It may be necessary to adjust the high voltage later to reduce the gain of the system.

7.4.3.2 Procedure to Adjust Pole Zero and DC Offset in Amplifier

Refer to the component layout diagram in Figure 7.11, and locate potentiometers R14 (the pole zero adjustment) and R15 (the DC offset). Connect the oscilloscope to the output of the "NEUTRON" amplifier on the pin socket. Turn on the 12-V supply and wait 2 minutes for the voltage to stabilize. Place the oscilloscope in the 100 mV/cm scale position.

To adjust the DC offset, place the oscilloscope in the autotrigger mode and ground the input. Adjust the vertical position to place the oscilloscope trace on the baseline. Return the oscilloscope to the DC position. Adjust R15 (DC offset) potentiometer to the zero volt level.

Proper adjustment of the pole zero requires a small neutron source to produce realistic pulses. If no source is available, a pulse generator may be used to insert a negative pulse to the "TEST" position TP2 on the 51 ohm resistor shown on Figure 7.11. Using the 100 mV/cm vertical scale and the 10 μ sec/cm time scale, adjust potentiometer R14 (pole zero adjust) so that the pulses return to the baseline in the shortest time. A very slight overshoot (positive pulses going slightly below the baseline) is desirable to lessen any effects of very long pulses produced by vibration.

7.4.3.3 Final Adjustment of Gain of System

The last step of the laboratory adjustment is to adjust all of the detector modules to the same approximate gain so that they are interchangeable. This is best accomplished by exposure to a neutron source. In the case of TEPCs, refill the counters to a 2- μ m-equivalent diameter using the manufacturers recommendations. A convenient gas filling system is available from Far West Technology.(a) Wait about an hour or so for the counter to equilibrate. (The TEPC counter always seems to undergo rapid gain changes in

(a) See Appendix A for additional information.

the first few minutes after it is filled.) Connect the output of the "NEURON" amplifier to an MCA. Ideally, the analyzer module should be used, but almost any 2048 channel good quality analyzer can be used. Then attach the TEPC detector modules to a 12-V power source, wait about 2 minutes for the high voltage to stabilize, and collect a spectrum with the TEPC next to a neutron source. Determine where the proton edge is, and adjust the high voltage to place the proton edge in about channel 256. This completes adjustment of the TEPC module. However, it is a good idea to repeat these measurements over the course of a week to determine the stability of the system and whether gain changes have occurred from deterioration of the fill gas in the counter. Be certain to change the value of IGUESS in the computer file WIRE.DAT to correspond to the value of the proton edge. This is easy to accomplish with any text editor or word processor, assuming that the operator is familiar with their operation.

The calibration of the ^3He proportional counter can be made with a less intense neutron source, because the counter is very sensitive to slow neutrons. In fact, with a very sensitive bare detector, a slow neutron peak can often be created by environmental neutrons. The procedures for calibrating the ^3He detector module are almost identical to those for the TEPC. Connect the proportional counter to the detector electronics using a SHV to SHV connector. Then connect a cable from the detector electronics to a 12-V supply and apply power to the unit. Wait 2 minutes for the high voltage supply to stabilize, then collect a spectrum with an MCA from the output of the "NEUTRON" amplifier. Carefully adjust the high voltage supply until the slow neutron peak occurs in channel 271. This completes the laboratory calibration of the detector modules. Be careful to turn off the 12-V supply before removing the SHV cable to the proportional counter to avoid damaging the input FET.

7.5 COSTS OF ALTERNATE SPECTROMETER DESIGNS

The information in Section 7.5 has been included because cost for the spectrometer may be an important consideration. Several alternative designs are listed so that the user can select the appropriate option depending on budget constraints.

The PNL prototype version described in Sections 7.3 and 7.4 is portable, rugged, and reliable in harsh operating conditions. This option requires some custom fabrication of printed circuit boards, and the persons assembling the spectrometer must have experience in electronic fabrication techniques. The PNL-designed circuitry for the detectors combines a preamp, amplifier, and high voltage power supply onto a single printed circuit that is less expensive than the NIMbin electronics. The first PNL prototype field spectrometer used high-quality components and was field tested under harsh operating conditions. Less expensive components can be substituted, but the circuitry might not be as reliable or rugged.

An option at the opposite extreme is to assemble the entire spectrometer from commercially available NIMbin electronic modules as discussed in Section 7.2. This option can be assembled by a health physicist with no training in electronics. However, this is the most expensive option. The least expensive option is to assemble a spectrometer using an IBM PC® compatible computer and NIMbin electronics already available at the facility. Only the detectors need to be purchased by using this option.

The following costs are estimated for each of the various design alternatives. These costs may vary considerably and may not be current. Also, considerable savings may be realized by large quantity purchases. This may be particularly true for fabrication of the PNL-designed circuitry by an off-site electronics manufacturer. The costs for a complete system are highly variable, depending on the desires of the user and price fluctuations in the necessary components. The costs below were estimated in January 1987 and may not be current. They may vary with locality. The following discusses three suggested options. Reference to any specific commercial product does not imply endorsement. These products are for purpose of illustration only, and other equally suitable products are available.

7.5.1 Costs of Detector Modules

The costs of the detector modules are given in Table 7.9. The least expensive option is to purchase only the detectors and use NIMbin electronics that may be found in many DOE facilities. Using only one detector, the minimum equipment costs would be about \$2100 to \$2600. For illustration, the costs associated with using only NIMbin electronics was estimated using EG&G

TABLE 7.9. Costs Associated with Various Options for the Detector Module(a)

<u>Equipment</u>	<u>Manufacturer</u>	<u>Cost</u>
Tissue Equivalent Proportional Counter	Far West Technology, 5-in.-dia, single wire counter	\$2560
³ He Proportional Counter	Reuter Stokes, 2-1/2-in.-dia, 2 atm He-3, 8 atm Ar	\$2100
Preamplifier (1 per detector)	EG&G Ortec, Model 142PC	\$665
Amplifier (1 per detector)	EG&G Ortec, Model 572	\$1260
	Model 570	\$750
	Model 575A	\$525
High Voltage Power Supply (1 per detector)	EG&G Ortec, Model 456	\$745
	Model 556	\$995
	Model 428	\$785
NIMbin and power supply	Berkeley Nucleonics, Model AP-3	\$1240
	EG&G Ortec, Model 4001M bin	\$895
	Model 495, 6-V supply	\$615

(a) See Appendix A for additional information.

Ortec equipment already in use at PNL. In this case, the most expensive option for both the TEPC and ³He detectors and associated NIMbin electronics would be about \$11,100. It is estimated that the PNL-designed electronics could be fabricated by an off-site manufacturer for less than \$1000 per module; this option is less expensive than using commercially available components. Thus, the total costs for the detector modules would be about \$3100 for the ³He detector module using a 10-atm tube and about \$3600 for the TEPC module using a 5-in.-dia spherical TEPC, using the PNL-designed circuitry.

7.5.2 Costs of the Analysis Module

The costs of components in the analysis module are listed in Table 7.10. The costs are listed for several options, including a 4-input MCA or a single input MCA. Several different multichannel buffers are listed; the Ortec Model 917 has a 4K memory and a slow ADC. This unit will operate at low count rates with a single detector. The more expensive Ortec Model 918 has an 8K memory and a faster ADC; it can operate with a single detector or four

TABLE 7.10. Costs of Components Used in the Analysis Module(a)

Equipment	Manufacturer	Cost
MCA Options-		
1 Input Multichannel buffer,	EG&G Ortec, Model 918	\$3620
	Model 917	\$2400
4 Inputs Multichannel buffer	EG&G Ortec, Model 918A	\$4020
Multiplexer, 4 inputs	EG&G Ortec, Model 476-4	\$1300
Computer Options-		
IBM PC® clone, 10 Mbyte hard disk, gas plasma display, math coprocessor	Grid Systems, GRiDcase® 3	\$4200
IBM PC® clone, 20 Mbyte hard disk, LCD display, math coprocessor	Grid Systems, GRiDcase® 3, Model 1263	\$2995
IBM PC® clone, 2 floppy disks, LCD display, math coprocessor	Zenith, Model Z183	\$2000
Aluminum suitcase, 24-in x 18-in x 9-in	Zero Halliburton	\$185
Low Voltage Power Supply	Berkeley Nucleonics, Model AP-3	\$1235
Cooling Fans, 4 each	Microboxer	\$85

(a) See Appendix A for additional information.

detectors simultaneously. This unit is fast enough and has enough memory to operate with intrinsic germanium gamma-ray spectrometers.

There are many different IBM PC® clones that could be used in the analysis module. The PNL prototype used A GRiDcase® 3 computer with a gas plasma display and a hard disk for permanent data storage. This unit works in harsh operating environments and is mechanically rugged. The gas plasma display is bright enough to be legible in almost any lighting condition. Unfortunately, this unit is more expensive than others. Other lap-top computers could be

used, but they may not be as rugged or reliable under hostile operating environments. Any IBM PC® compatible computer could be used that includes 640K of random access memory (RAM), a math coprocessor, a 25 line by 80 character display, and two floppy disk drives or a single hard disk. The memory disks are required for storage of the large operating computer program and for data storage. Computers with liquid crystal displays (LCDs) may not be as legible or those with a gas plasma display in some lighting conditions, but they are functional and less expensive. Other IBM PC® clones with floppy disk drives and LCDs range in price from about \$1000 to \$3000. Also, less expensive machines may require that the operator be more familiar with computers and may be more difficult to operate. However, the PNL software should be compatible with almost any IBM PC® clone. The authors have not determined whether these clones will function in harsh operating conditions.

The least expensive analysis module would include a single input Ortec 917 multichannel buffer, the least expensive IBM PC® clone with dual floppy disks and an LCD, and an inexpensive power supply. Total costs of components for the analysis module for this least expensive option would be about \$6000. The costs of the components used in the first PNL prototype analysis module with 4-input MCA and the GRiDcase® computer with a gas plasma display was about \$15,000, excluding the costs of assembly and calibration.

7.5.3 Costs of System

The costs for a complete system are highly variable, depending on the desires of the user and price fluctuations in the necessary components. These costs were estimated in January 1987 and may not be current. They may vary with locality. The following discusses three suggested options. Reference to any specific commercial product does not imply endorsement. These products are for purpose of illustration only, and other equally suitable products are available.

If budget constraints are the primary concern, an inexpensive system with only a single detector is suggested. This system would use a single detector module, consisting of either a 2-1/2-in.-dia ³He proportional counter or a 5-in.-dia spherical TEPC. It would use the PNL-designed circuits for the preamplifier/amplifier/high voltage power supply. The analysis module would consist of an Ortec Model 917 ADCAM and a bottom-of-the-price-range IBM PC®

lap-top clone with floppy disks and a LCD display. This option would cost \$8000 to \$10,000 for the components; no estimate is made for the costs associated with assembling and testing the system.

This recommendation is subject to the following caveats. The inexpensive IBM PC® clones have not been tested under field exposure situations, and the user may experience unexpected problems (for example, sensitivity to power line noise or temperature). Using a single detector may require a longer time to complete measurements, resulting in a greater disruption of operations. Also, the costs of the ^3He tubes is proportional to the amount of ^3He in the counter. Less expensive tubes are less sensitive, and longer measurements will be required. Finally, unless the user is trained in computer programming, the modifications required to convert the computer program may be expensive and time-consuming.

If cost is not the primary concern, the following option based on a 4-input analysis module is suggested. The analysis modules should contain the 4-input Ortec Model 918A multichannel buffer and an Ortec Model 476-4 multiplexer. A GRiDcase® Model 1263 computer with a back-lit LCD, a 20 Mbyte hard disk, and a math coprocessor is suggested. These components are estimated to cost between \$16,000 and \$18,000; no estimate has been made for the costs of assembling and testing the system.

If ease of use and maximum versatility are of primary concern, it is suggested that the spectrometer system be patterned after the PNL prototype system. Because of introduction of new models, a GRiDcase® computer with a gas plasma display and a 20 Mbyte hard disk may be less expensive in the near future. Also, it is suggested that higher pressure ^3He proportional counters be used to minimize the time required to make measurements. The components for this option are estimated to cost between \$18,000 and \$20,000; no estimate has been made for the costs of assembling and testing the system.

This last option would be the most versatile and allow for future expansion to other detectors, if desired later. The use of two more sensitive detectors would allow accurate measurements in only a few hours, even with dose rates below 1 mrem/h. This would result in less interference with production schedules. Furthermore, this system has been demonstrated to function satisfactorily for field measurements in the work place.

Some cost savings could be achieved by large volume purchases. It is difficult to make accurate estimates, because most manufacturers are hesitant to give firm quotes for large purchases. However, in lots of 20 or more, a 15% discount is usually quoted for electronic components. For example, in lots of 10 the cost for the 5-in-dia single wire TEPC could be reduced to \$2300. A less sensitive ^3He proportional counter would cost \$1900. For purchases of 4 or more units, the cost of the Berkeley Nucleonics Portanim, Model AP-3 would be \$1185. Perhaps the most important savings could result from the mass production of the PNL-designed circuits by an independent manufacturer: the PNL-designed printed circuits could cost between \$600 and \$1000 per detector module if mass produced.

For 10 or more units, the PNL prototype spectrometer could be produced for a cost of \$15,000 to \$20,000. Although this may seem expensive, these costs are competitive with gamma-ray spectrometers using commercial MCAs and intrinsic germanium detectors. In fact, the field spectrometer could be used as a gamma ray spectrometer with the purchase of vendor supplied software and a gamma-ray detector. The field spectrometer is easier to operate and is more rugged than most comparable commercial MCAs.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Advisory organizations, such as the ICRP, the ICRU, and the NCRP, have recommended changes in existing radiation protection standards. These proposed changes include

- increasing existing values of neutron quality factors
- redefining quality factor as a function of lineal energy rather than as a function of linear energy transfer
- adopting effective dose equivalent methodology as outlined in ICRP Publication 26 (ICRP 1977).

Knowledge of the neutron energy spectra in the workplace where personnel are exposed to neutrons makes it possible to determine the effects of these proposed changes. Detailed spectral measurements offer many advantages. It is possible to increase the accuracy of existing neutron dosimetry by exposing personnel dosimeters on phantoms in the workplace where the neutron energy spectra, average quality factor, and dose equivalent rate have been determined from spectral measurements. Measurements of the flux as a function of incident neutron energy or of the dose distribution as a function of lineal energy make it possible to calculate the effects of future changes in quality factors. Finally, effective dose equivalents can be estimated from knowledge of the irradiation geometry and neutron energy spectra or depth-dose information.

Obviously, a need exists for a simple, portable neutron spectrometer that can quickly and accurately determine spectra in the workplace. As demonstrated in this report, the PNL field spectrometer meets this need.

The prototype field spectrometer developed at PNL can make four simultaneous measurements using two different types of detectors: ^3He proportional counters and TEPCs. These detectors were selected for their ease of use (no complex set-up or calibration is required), simplicity of data analysis (data is analyzed by a computer without human intervention), ease of calibration (both types are self-calibrating), and accuracy of measurement over fission energies. Using two detectors with completely different methodologies for determining quality factors and dose equivalent adds credibility

to the accuracy of the measurements. Also, the TEPC directly measures lineal energy distributions, so that quality factors can be determined directly if quality factors are redefined as a function of lineal energy.

Laboratory tests were conducted by exposing the detectors to a calibrated ^{252}Cf neutron source. Measurements with a 5-in.-dia spherical TEPC agreed within 6% of the accepted dose equivalent rate from the calibrated neutron source. However, extensive testing revealed that TEPCs with poor resolution and changing gas gains could give results with errors of more than 20%. It is recommended that the TEPCs used for the field spectrometer be tested at a constant dose rate over a period of several weeks to determine their operating life-time and limits of accuracy before they are used for measurements in the workplace.

Measurements were also conducted by exposing the ^3He detector to the calibrated neutron source. For the first prototype, the ^3He proportional counter contained 5 psia of ^3He and 34 psia of argon in a 2-1/2-in. dia by 12-in.-long cylinder. This tube was selected because it was available at PNL and could be easily transported. [Pressurized containers with more than 40 psia are considered hazardous materials by the U.S. Department of Transportation (DOT), and DOE has instituted strict controls for their use.] As explained in Section 6.0 of this report, this tube is not well suited for measurements of neutrons with energies of 5 MeV, because only 2% to 3% of the incident neutrons deposit all of their energy in the tube. Nevertheless, measurements demonstrated that this tube determined the dose equivalent rate within 8% and the average quality factor within 4% for fission spectra.

The field spectrometer was also tested in two plutonium processing facilities at Westinghouse Hanford Company, Richland, Washington, and at the LANL. The tests revealed that the PNL prototype field spectrometer performed as well as other spectrometers that use NIMbin electronics that are much heavier and more difficult to use.

Tests in the laboratory and in plutonium facilities suggested that several improvements could be added to make the PNL field spectrometer more accurate and easier to use in very low dose rates. The present detectors require an exposure to at least 10 mrem or more to obtain good statistical accuracy and calibration values. In many of the fields measured in plutonium

facilities, the neutron dose equivalent rates are about 0.1 mrem/h, so excessively long counting times are required. It would be highly desirable to use a built-in alpha source in the TEPC for energy calibration. Counters with a ^{244}Cm alpha calibration source are commercially available but were not used initially because of the problems involved in transporting transuranic radioactive sources. The computer analysis program for the TEPC is being modified to allow the use of a built-in alpha source for energy calibration, but this will add to the complexity of the measurement process.

As mentioned above, the ^3He proportional counter was limited to a total pressure of less than 40 psia to avoid hazardous materials shipments, but it would be highly desirable to use higher pressures to increase the intrinsic efficiency of the tube for higher-energy (5 MeV) neutrons. In December of 1987, the Reuter-Stokes Division of General Electric Co. obtained an exemption from the DOT to allow transportation of higher pressures for ^3He proportional counters. If enclosed in an appropriate container, the higher-pressure tubes are not classified as hazardous materials. Therefore, it is recommended that higher-pressure proportional counters be used in measurements for fission energy neutrons. A tube containing a total of 10 atm pressure is being used at PNL. This tube contains 6 times more ^3He and has an intrinsic efficiency of 10 times higher than the 5 psia tube used in the prototype, so the new tube should be 60 times more sensitive to 5 MeV neutrons. This should allow measurement of the neutron energy spectra in a few hours, even at rates of less than 1 mrem/h.

Because the field spectrometer contains two microprocessors, it has the limitations of most microcomputers: power line transients can cause these computer to malfunction. This occurred during the tests at Los Alamos, and data was lost during an overnight run. To mitigate this problem, the data is analyzed every half hour. If a preset limit for statistical accuracy is achieved, the computer automatically writes out the results of the analysis and the raw data to a hard disk for permanent storage.

The PNL prototype field neutron spectrometer has been used to accurately determine the quality factor and dose equivalent rate as well as detailed energy spectra for neutrons with energies between 50 keV and 5 MeV. The field spectrometer weighs 40 lb and fits easily into an average sized

suitcase for portability. Extensive work went into developing the computer control, data transfer, and graphics capabilities of this instrument. The existing "driver" program in the field spectrometer makes it easier to use than most of the existing MCA. Almost any detector can be attached to the field spectrometer. A multisphere spectrometer and NE-213 liquid scintillator spectrometer will be added to the next version of the field spectrometer.

Moreover, if suitable FORTRAN data analysis codes are available, this spectrometer unit can be used for many other applications, such as safeguards or waste assay. By attaching sodium iodide scintillator or intrinsic germanium gamma-ray detectors, it would be very easy to produce a gamma-ray spectrometer. This could be used to determine isotopic enrichments for ^{235}U , plutonium composition for safeguards, or isotope identification and quantification for waste assay. The versatility and simplicity of operation of the PNL field spectrometer make it useful for many other applications.

9.0 REFERENCES

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APPENDIX A

POSSIBLE SOURCES OF SUPPLIES PNL FIELD NEUTRON SPECTROMETER

APPENDIX A

POSSIBLE SOURCES OF SUPPLIES PNL FIELD NEUTRON SPECTROMETER

This appendix lists possible sources of supply for some of the major components used in the field spectrometer, or equivalent components. These suppliers are listed for illustration only, and equivalent products can be obtained from vendors other than those listed. Mention of these products should not be considered as endorsement by PNL or DOE.

<u>Manufacturer</u>	<u>Components</u>
Berkeley Nucleonics Corp. 1198 Tenth St. Berkeley, CA 94710-9988 (415)527-1121	portanims
Canberra Industries One State Street Meriden, CT 06450 (203) 238-2351	multichannel analyzers, NIMbin electronics
EG&G Ortec, Inc. 100 Midland Road Oak Ridge, TN 37830 (615)482-4411	NIMbin electronics, multichannel analyzers
Far West Technology 330D South Kellogg Ave. Goleta, Ca 93117 (805)964-3615	tissue equivalent proportional counters
Grid Systems Corp. 2535 Garceia Ave. P.O. Box 7535 Mountain View, CA 94039-7535 (415)656-4700	GRiDcase® computers
Harshaw/Filtrol 681 Cochran Road Solon, OH 44139 (216)248-7400	³ He proportional counters

<u>Manufacturer</u>	<u>Components</u>
Hecox and Associates 4614 W. Yellowstone Kennewick, WA 99336	printed circuit boards
IBM Corporation Personal Computers P.O. Box 1328-C Boca Raton, FL 33432	personal computers
Microsoft Corporation 10700 Northup Way Box 97200 Bellevue, WA 98009	MS-DOS software
Nuclear Data Inc. Instrumentation Division Golf and Meachum Roads Schaumburg, IL 60196 (312)884-3621	NIMbin electronics, multichannel analyzers
Power Designs, Inc. 1700 Shames St. Westbury, NY 11590 (516) 333-6200	power supply
Reuter-Stokes Division of General Electric Edison Park Twinsburg, OH 44087-2398 (216)425-3755	³ He proportional counters
Tektronix, Inc. P.O. Box 500, Y3-314 Beaverton, OR 97027 (800) 547-6711	oscilloscopes
Tennelec, Inc. 601 Oak Ridge Turnpike P.O. Box 2560 Oak Ridge, TN 37830-2560 (615) 483-8405	NIMbin electronics, multichannel analyzers
Word Perfect Corporation 288 West Center Street Orem, UT 84957 (801) 225-5000	computer software

APPENDIX B

SETUP AND OPERATING INSTRUCTIONS,
PNL FIELD NEUTRON SPECTROMETER

APPENDIX B

SETUP AND OPERATING INSTRUCTIONS, PNL FIELD NEUTRON SPECTROMETER

Set-up and operating instructions for the field neutron spectrometer are contained in procedures 1 through 7 contained in this appendix. Instructions are included for operating both the version of the field spectrometer that uses commercial electronics and the version that uses PNL-designed electronic circuitry built into the detectors. Sufficient detail is included for an operator to manipulate the field spectrometer without any other training, but it is recommended that the operator be familiar with the theoretical material presented in Sections 3.0 and 4.0 as well as the material presented in Section 7.0 on construction of the spectrometer. In event of trouble, this background material will aid the operator in diagnosing and solving the problem. The operating instructions are written assuming that the operator has had little experience with computers and that the spectrometer system has been adjusted and thoroughly tested in the laboratory before the operator takes it into the field. The spectrometer system can be adjusted in the field if the operator has some knowledge of the MS-DOS® operating system on the computer, but it is much easier to make final adjustments in the laboratory.

Operating Procedures/PNL Field Neutron Spectrometer

PROCEDURE 1

SETTING UP THE FIELD SPECTROMETER

Detailed instructions are not necessary to operate the PNL field spectrometer. Specific operating instructions are displayed by the computer when needed by the operator. It is suggested that the operator examine the procedures included in the appendix to become familiar with the instructions displayed on the computer screen. The following is a step-by-step procedure for setting up the field spectrometer.

<u>STEP #</u>	<u>ACTION REQUIRED</u>
1.1	Select a location for the analysis module (the suitcase) where it will not interfere with normal work procedures and is near a source of 120 VAC power.
1.2	Select the desired detector locations for measurements. COMMENT: These are typically near glove boxes.
1.3	Mount detectors on tripods or other stable supports, so that they can be positioned at the desired locations.
1.4	Secure the tripods with tape or some method such that they will not be inadvertently moved during normal working operations.
1.5	If the ^3He spectrometer is to be used, follow steps 1.6 to 1.13; if the TEPC detector is to be used, follow steps 1.14 to 1.19.
1.6	^3He DETECTOR MODULE - The following steps 1.7 through 1.13 are for setting up the ^3He detector modules.
1.7	Place the ^3He proportional counter inside a lead and cadmium shield (used to prevent pulse pile-up as discussed in Section 3.2.5). Place the detector and shield assembly on the support stand.
1.8	Check to make certain that the light on the side of the support stand is not illuminated (indicating there is no power applied to the unit).
1.9	Connect the proportional counter to the support stand using a short SHV coaxial cable.

Operating Procedures/PNL Field Neutron Spectrometer

- 1.10 Connect the cables from the detector modules to the analysis module.
NOTE: The power to the detectors is provided by a preamp power cable with D connectors on each end. There are male and female ends on the D connectors.
- 1.11 Connect the signal cable (the coaxial cable with BNC connectors) to the detector and analysis modules.
- 1.12 Route the cables back to the analysis module.
CAUTION: If the cables are placed where workers could trip over them, tape them down. In aisles or locations where there may be considerable foot traffic, place a piece of plastic or paper over the cables, then tape the edges to the floor.
- 1.13 Connect the cables from the ^3He detector module to the D connector and BNC signal cable on either port 1 or port 2 at the analysis module. This completes the set up for the ^3He detectors.
- 1.14 TEPC DETECTOR MODULE - The following steps are suggested for setting up the TEPC module.
- 1.15 Connect the power cable to the D connector on the back of the TEPC detector module if the PNL prototype is used.
- 1.16 Attach the signal cable to the BNC connector for the signal output on the base of the TEPC detector module. If commercial components are used, connect the TEPC detector to the preamplifier as discussed in Section 7.4.1.
- 1.17 Route the cables to the analysis module.
NOTE: Tape the cables down to prevent tripping hazards, as necessary.
- 1.18 At the analysis module, connect the cables from the TEPC detector to the D connector and the BNC signal connector.
NOTE: The TEPC detectors must be attached to port 3 or port 4 on the analysis module for the computer program to properly analyze the data. This completes the set up of the TEPC detector module.

This completes Procedure 1, Setting up the Field Spectrometer.

Operating Procedures/PNL Field Neutron Spectrometer

PROCEDURE 2 OPERATING THE COMPUTER

This procedure outlines the steps necessary to connect and power-up the computer used in the analysis module.

STEP #	ACTION REQUIRED
2.1	At the analysis unit, connect the power cable from the socket provided to a 120 VAC wall socket.
2.2	Turn on the illuminated switch at the left side of the analysis module. NOTE: This provides power to the detectors and the Ortec ADCAM(a) unit.
2.3	Check the ribbon cable at the back of the lap-top computer to ensure that both ends are connected.
2.4	Check to ensure that the computer power supply (located on the left side of the analysis module) is connected to 120 VAC and that the computer is connected to the power supply. NOTE: The power input connector on the computer is located on the back of the computer near the left side. CAUTION: Before moving on to the next step, wait about two minutes to allow the high-voltage power supplies and amplifiers to stabilize.
2.5	Open the display by opening the catches on each side of the computer.
2.6	Turn on the computer using the switch on the right rear of the computer.
2.7	If the analysis software has been properly installed, the autoexec file will direct the computer to automatically start the analysis program.
2.8	If this is not the case, you must find the analysis program using MS-DOS® commands.

Operating Procedures/PNL Field Neutron Spectrometer

- 2.9 Type "dir/p," then press the return key to obtain a listing of the programs in the directories.
- 2.10 Once you locate the analysis program called RUNNER.EXE, simply type RUNNER and press the return key.

NOTE: The computer software will automatically control the operation of the analysis module. The program will acquire data, transfer the raw data from the Ortec ADCAM unit to the computer, analyze the results, and then display them.

If you press a STOP key, or if the desired degree of statistical accuracy is achieved, the program stops accumulating data, analyzes it once more, then writes out the analyzed results and raw data to a data file.

Each port has its own files. For example, the data from port 1 is called PORT1.DAT for the first measurement and PORT1A.DAT for the second measurement. Each data file also writes out when the measurement was started and when it ended. Thus, the time of the measurement and the acquisition port number (e.g., PORT1.DAT, PORT2.DAT, etc.) are used to identify individual measurements.

This completes Procedure 2, Operating the Computer.

Operating Procedures/PNL Field Neutron Spectrometer

PROCEDURE 3

STARTING DATA COLLECTION

Use the following steps to collect data. Remember, the START and STOP keys are the program function keys labeled F1 to F10 on the keyboard. These keys control the program, and other keys are locked out to prevent inadvertent errors.

Once the program starts, the computer displays the logo shown in Figure B.1, which identifies the specific version of the program being used.

```
*****
*
*
*
*
*      Neutron Spectrometry
*      System
*
*      Developed for DOE
*      by Pacific Northwest Laboratory
*
*      LW Brackenbush, WD Reece, RI Scherpelz
*      SD Miller, JE Tanner, JS Durham
*
*
*
*
*
*
*      Version 1.0
*
*      Hit any key to continue
*
*****
```

FIGURE B.1. Logo Display Shown at Start of the Neutron Spectrometry System Program

Operating Procedures/PNL Field Neutron Spectrometer

STEP #	ACTION REQUIRED
--------	-----------------

3.1	Press any key on the computer keyboard to continue.
-----	---

COMMENT: The program then displays the introductory message shown in Figure B.2. It reminds the operator to connect the ^3He detector to port 1 or 2 and the TEPC detector to port 3 or 4.

WARNING: Heed the warning on the screen about waiting 5 seconds after each read or write to the hard disk in the computer. A head crash could result if the computer is turned off during a data transfer to the disk, and data could be lost.

INTRODUCTION

This system is set up for He-3 and TEPC detectors. The system Automatically collects data, analyzes it, and displays the results. The process is repeated until a desired level of statistical accuracy is reached or until the user terminates data collection.

After collecting data, the system automatically analyzes the data and displays the results. The system also stores the data on the hard disk in the computer, and it can be retrieved later if desired.

WARNING! DO NOT TURN OFF THE POWER UNTIL AT LEAST 5 SECONDS AFTER THE DATA TRANSFER IS COMPLETE AND THE RED LIGHT ON THE SIDE OF THE COMPUTER GOES OUT.

SET-UP INSTRUCTIONS

Make certain the He-3 detector is plugged into port 1 or 2 and the TEPC detector is plugged into port 3 or 4.

HIT ANY KEY TO CONTINUE

FIGURE B.2. Introduction Message Displayed on Computer Screen

Operating Procedures/PNL Field Neutron Spectrometer

- 3.2 Press any key to continue.
COMMENT: The program displays the "WHAT WOULD YOU LIKE TO DO?" message shown in Figure B.3.
- 3.3 If you wish to acquire data with the ^3He detector, proceed to Procedure 4.
- 3.4 If you wish to acquire data with the TEPC detector, proceed to Procedure 5.

WHAT WOULD YOU LIKE TO DO?	
PRESS KEY:	TO:
F1	TO START HE-3 ON PORT1
F3	TO START HE-3 ON PORT2
F5	TO START TEPC ON PORT3
F7	TO START TEPC ON PORT4
F10	TO STOP PROGRAM

FIGURE B.3. Choices for Data Acquisition -
"What Would You Like to Do?" Message

This completes Procedure 3, Starting Data Collection.

Operating Procedures/PNL Field Neutron Spectrometer

PROCEDURE 4

STARTING DATA ACQUISITION BY THE ^3He DETECTOR

This section provides details for starting data collection by the ^3He detector. The program assumes that the ^3He detector modules are connected to port 1 or port 2.

STEP #	ACTION REQUIRED
--------	-----------------

4.1	Press F1 to start data collection on the detector attached to <u>port 1</u> .
-----	---

	Press F3 to start data collection on the detector attached to <u>port 2</u> .
--	---

NOTE: Several keys can be pushed in sequence to start data collections on several ports.

COMMENT: After pressing either F1 or F3, the information shown in Figure B.4 will appear on your screen. It shows the STATUS of the measurements. The first line shows current date and current Greenwich Mean Time. In the example shown in the figure, under port 1, the listing of the last analysis and next analysis shows that the analog-to-digital converter (ADC) has been turned on, but no data has yet been analyzed.

4.2	Record the time and date that data collection was started and the port number of the detector.
-----	--

COMMENT: This information will be used to identify the output file containing the data.

COMMENT: After 30 seconds, the program automatically transmits the data collected in the Ortec ADCAM unit to the computer. Next, the computer displays "ONE MOMENT PLEASE" for 23 seconds while data are being transferred from the ADCAM unit to the computer memory. The computer then displays a graph of the data as shown in Figure B.5.

Operating Procedures/PNL Field Neutron Spectrometer

```
Current time is:  2/ 2/1988  15:10:24  GMT

      +++++ He-3 System +++++
      ***** port 1 *****      ***** port 2 *****
Last Analysis    2/ 2/1988  15:10:14  GMT      --- not      ---
Next Analysis    2/ 2/1988  15:10:44  GMT      --- active    ---

Average Energy    .000 +/-   .000 MeV      -----
Q                 .0 +/-     .0            -----
Dose Equivalent Rate  .0 +/-   .0 mrem/hr    -----
=====
      +++++ TEPC System +++++
      ***** port 3 *****      ***** port 4 *****
Last Analysis    2/ 2/1988  15:09:51  GMT      --- not      ---
Next Analysis    2/ 2/1988  15:39:51  GMT      --- active    ---

Average Energy    2.426 +/-   .348 MeV      -----
Q                 10.6 +/-    1.1            -----
Dose Equivalent Rate  60.7 +/-  23.0 mrem/hr  -----
=====
Press:           Press:
F2 to STOP port 1 and analyze data    F6 to STOP port 3 and analyze data
F3 to START port 2 collection          F7 to START port 4 collection
F1 to analyze port 1 and CONTINUE      F5 to analyze port 3 and CONTINUE
```

FIGURE B.4. "STATUS" Message Displayed on the Computer Screen

- 4.3 Examine these data carefully.
NOTE: There should be a slow neutron peak above the first tick mark on the Channel Number scale. If no data is displayed, either there is a malfunction or the dose rate is so low that several days of data collection will be required.
- 4.4 If no data is collected, press the appropriate STOP key (F2 or F4) to stop data collection.
- 4.5 If data collection has been stopped, proceed to the trouble-shooting guide in Section 5.4.

2/ 2/1988 15:10:44 GMT

He-3 RAW DATA

Hit any key to continue

FIGURE B.5. Graph of the Raw Data from the ^3He Detector

4.6

If data is being collected, proceed by pressing any key.

NOTE: If you do not respond within 2 minutes, the computer will automatically continue with next step.

COMMENT: Next, the computer will display the graph shown in Figure B.6. The vertical axis is the neutron flux density with dimensions of neutrons/s/cm²; the horizontal axis is the incident neutron energy in 100 keV bins. With only 30 seconds of data acquired, the graph will not be very accurate. Examine the graph carefully; if there is a distinct peak at 760 keV, there is a

FIGURE B.6. Graph of the Neutron Flux Measured by the ^3He Detector

possibility of pulse pile-up. Also, if there is a large flux in the first 100 keV bin, there is a good possibility that gamma pile-up is occurring, and more shielding around the detector is required. Future versions of the program will automatically warn the operator and compensate for pile-up, but this automation was not completed in time to be included in this software. If problems are found, stop the analysis using Procedure 6.

- 4.7 If no problems are found, proceed by pressing any key other than a function key.

Operating Procedures/PNL Field Neutron Spectrometer

NOTE: If you do not press a key within 2 minutes, the computer will proceed on its own.

COMMENT: The computer then returns to the STATUS display described at the beginning of Procedure 3 and shown in Figure B.4. However, the display will have been updated, and the next data analysis will automatically be initiated in 30 minutes. The computer displays the current time and the time of the next data analysis. The computer has also updated the STATUS display to show the results of the last data analysis, including the average energy in MeV, the mean quality factor, the dose equivalent rate in mrem/h, and the standard deviations for each quantity as a result of counting statistics.

At the end of 30 minutes, the computer then initiates another data transfer and analysis sequence. As before, the sequence will include graphs of the raw data and the analyzed neutron energy spectrum. If the operator does not respond within 2 minutes to any questions asked by the computer, the program will automatically proceed until it returns to the STATUS display shown Figure B.3. This process is repeated every 30 minutes until the operator stops data collection, as described in Procedure 6, or until a preset statistical accuracy limit has been achieved. Once the accuracy limit is achieved, the program automatically writes out the results to the hard disk for permanent storage in files labeled PORT1.DAT or PORT2.DAT, and so forth. The STATUS display shows the average energy, quality factor, and dose equivalent rate, but the time for the next analysis is replaced with the statement "port 1 [or port 2] not active."

When all the data acquisition has stopped, the program displays the "WHAT WOULD YOU LIKE TO DO?" message shown in Figure B.3.

This completes Procedure 4, Starting Data Acquisition for the ^3He Detector.

Operating Procedures/PNL Field Neutron Spectrometer

PROCEDURE 5

STARTING DATA ACQUISITION FOR THE TEPC DETECTOR

Data acquisition and analysis for the TEPC detectors can be started by following this procedure.

STEP #	ACTION REQUIRED
--------	-----------------

5.1	Press the F5 function key for a TEPC connected to port 3, or the F7 function key for a TEPC connected to port 4 to begin data acquisitions for the TEPC detectors.

COMMENT: As in the case of the ^3He detector, the program automatically collects data for 30 seconds. Then the program displays the message "ONE MOMENT PLEASE" for 23 seconds while the raw data is being transferred from the Ortec ADCAM unit to the computer memory. After the data transfer is complete, the program displays the message "STARTING DATA ANALYSIS ON PORT 3" [or PORT 4 as appropriate].

The program then displays a graph of the "TEPC RAW DATA" as shown in Figure B.7.

5.2	Examine the graph carefully.

NOTE: If there is no data, especially in the first few channels, a malfunction has occurred or no radiation field is present.

5.3	If no data is being collected, proceed to Procedure 6 to stop the data analysis.

5.4	If there is data being acquired, please note the approximate channel number for the proton edge.

COMMENT: The proton edge is a sharp discontinuity in the raw data that usually occurs at about channel 250.

5.5	Press any key to proceed.

NOTE: If you do not press a key within 2 minutes, the computer continues to this next step.

Operating Procedures/PNL Field Neutron Spectrometer

2/ 2/1988 16:47:44 GMT

TEPC RAW DATA

Hit any key to continue

FIGURE B.7. Graph of Raw Data from TEPC Detector

COMMENT: The computer program then responds by displaying the message "CONTINUING TEPC ANALYSIS ON PORT 3" [or PORT 4 as appropriate]. The program then has two alternatives:

1. If there is not sufficient data to find a proton edge, or if the value of IGUESS in the data file WIRE.DAT is incorrect, the program will print a warning message and proceed with the data analysis using the last value input for IGUESS. If the value of IGUESS is incorrect, modify it using a text editor, but first exit the program by using Procedure 6 below.

Operating Procedures/PNL Field Neutron Spectrometer

2. If the program finds the proton edge, it proceeds to graph the data in the vicinity of the value given for IGUESS in the data file WIRE.DAT.

EXAMPLE: An example of the graph of the proton edge is shown in Figure B.8. Here the vertical axis shows the square root of the dose distribution, and the horizontal axis shows the data channel number. The plus signs represent the actual data, and the line through the data represents the Fourier smoothed data. The vertical dashed line shows the position the program picked for the proton edge or proton drop point. The number by the vertical dashed line is the channel number for the proton drop point as determined by the program. If the data is badly scattered, it may be a good idea to record this number to see how it changes as more data is acquired, and to compare it with previous runs to see whether it has changed dramatically.

NOTE: For low doses below about 20 mrem, the data accumulated may be insufficient to find the proton drop point properly. In this case, the program will use the previously input value from IGUESS. If the gain of the TEPC has shifted, some error may be introduced, and the user is advised to reanalyze the data in the laboratory.

5.6 To continue, press any key.

NOTE: If you do not respond within 2 minutes, the program will automatically continue on to the "STATUS" message shown in Figure B.4. As in the case of the ^3He detector, the "STATUS" message is updated. The time for the next analysis is displayed under the "TEPC System" caption in the "STATUS" display. The "STATUS" display also contains the last analyzed values for the average energy in MeV, average quality factor, and dose equivalent rate in mrem/h. The value selected for the average energy is only

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FIGURE B.8. Graph of the TEPC Data Near the Proton Edge

approximate at this time. The bottom lines give instructions on how to proceed.

- 5.7 To reanalyze the data, press key F5 for port 3 or key F7 for port 4.

COMMENT: The program continuously reanalyzes the data and updates the "STATUS" display every 30 minutes. Although the program displays the graphs and asks for input from the operator, no human intervention is necessary. The process is repeated every 30 minutes until a desired degree of statistical accuracy is achieved, or until the operator stops the data acquisition, as described in Procedure 6.

This completes Procedure 5, Starting Data Acquisition for the TEPC Detector.

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PROCEDURE 6

STOPPING DATA ACQUISITION AND STORING DATA

Data acquisition may be stopped any time the program displays the "STATUS" message. The bottom lines of the "STATUS" message describe ports that are still active and give instructions on which function keys to use to stop the data acquisition. For example, if port 4 is active, the "STATUS" message displayed is to push "F8 to STOP port 4 and analyze data." The even numbered function keys stop data acquisition:

- Function key F2 controls port 1.
- Function key F4 controls port 2.
- Function key F6 controls port 3.
- Function key F8 controls port 4.

STEP #	ACTION REQUIRED
--------	-----------------

6.1	Press the desired even numbered function key to stop data collection on the data port.
-----	--

COMMENT: Once the even function keys are pressed, the program activates the analysis sequence described in Procedure 4 for the ^3He detectors on ports 1 and 2 and in Procedure 5 for the TEPC detectors on ports 3 and 4. The program shows the message "ONE MOMENT PLEASE," then shows the graphs described above. At the end of the data analysis, the program displays the message "CLOSING PORT 1" [or ports 2, 3, or 4 as appropriate]. The program then returns to the "STATUS" display. If all of the ports are closed, the program displays the message "WHAT DO YOU WANT TO DO?" as described in Procedure 3.

6.2	If the "WHAT DO YOU WANT TO DO?" message shown in Figure B.3 is displayed, select the desired option.
-----	---

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COMMENT: At this point, the operator can move the detectors and start new measurements, or the program can be terminated by pressing key F10. The control of the computer is then returned to the MS-DOS® operating system.

This completes Procedure 6, Stopping Data Acquisition and Storing Data.

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PROCEDURE 7

USING WORDPERFECT®

If WordPerfect® is installed in the computer, it is possible to look at the data files using the following commands.

CAUTION: You may look at the data files, but do not change them with the WordPerfect® program: Look but don't touch!

STEP #	ACTION REQUIRED
--------	-----------------

7.1	Type the MS-DOS® command "dir" to find out which directory the data files are in.
-----	---

7.2	Use the change directory command "cd" and the directory command "dir/p" to find the WordPerfect® program.
-----	---

NOTE: The program is usually found as WP.EXE.

7.3	Once you have found the WordPerfect program, type "wp" and press the return key to execute it.
-----	--

7.4	Simultaneously press Shift and F10 to retrieve the desired data file.
-----	---

NOTE: To retrieve the data file, you must specify the names of the directories and the path used to get to the directory in which the data file is stored. For example, if WordPerfect® is in your main directory and the data file is in the directory DEMO, you can type

demo\port3.dat

to retrieve the data file, port3.dat. You can use the arrows to move around in the data file to examine the various parts. The first line in the data file gives the port number, the date, and time the measurement was started. The second line gives the date and time the measurement was stopped. The date and time are used to identify each measurement. The third line contains the following numbers: the average energy with its standard deviation, the average quality factor with its standard deviation, and finally the dose equivalent rate and its standard deviation. The fourth line

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and all the remaining lines contain eight columns. The first number is the live time in seconds, the second number is the clock time in seconds, and all remaining numbers are the counts per channel recorded by the multichannel analyzer (MCA).

- 7.5 Press F7 (exit) to exit from the WordPerfect® program.

COMMENT: The program will then inquire
Save document(Y/N):Y

- 7.6 Reply by pressing n (no).
The program then inquires

Exit WP(Y/N):N

- 7.7 Reply by pressing y (yes). The program then returns control to the MS-DOS® operating system.

CAUTION: Wait at least 5 seconds after exiting the WordPerfect® program before turning off the computer, otherwise a head crash on the hard disk may occur.

This completes Procedure 7, Using WordPerfect®.

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