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Neutron Dose and Energy Spectra Measurements at Savannah River Plant

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August 1987

Prepared for
E. I. du Pont de Nemours and Company
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with the U.S. Department of Energy
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Pacific Northwest Laboratory
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Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

Increased concern about the accuracy of neutron dosimetry and neutron quality factors has led to recommendations by the International Commission on Radiological Protection (ICRP) and the National Council for Radiation Protection and Measurements (NCRP) to increase quality factors. The ICRP recommended in 1985 to increase quality factors for fast neutrons from 10 to 20. The NCRP is considering similar recommendations. It is expected that the U.S. Department of Energy (DOE) will adopt any recommendations by the NCRP to increase quality factors.

Because any of the proposed changes would impact the operation of the Savannah River Plant (SRP), where some workers have a high potential for significant neutron expsoure, the SRP contracted with Pacific Northwest Laboratory (PNL) to verify the accuracy of neutron dosimetry at the plant.

Energy spectrum and neutron dose measurements were made at the SRP calibrations laboratory; the 221-H Area, B-Line; 221-F Area, B-Line, 221-F Area, Plutonium Storage; K-Reactor shield door; californium loadout and shipping areas; and 773-A Building.

The energy spectra measurements were made using multisphere or Bonner sphere spectrometers, ^{3}He spectrometers, and NE-213 liquid scintillator spectrometers. Neutron dose equivalent determinations were made using these instruments and others specifically designed to determine dose equivalent, such as the tissue equivalent proportional counter (TEPC). Survey instruments, such as the Eberline PNR-4, and the thermoluminescent dosimeter (TLD)-albedo and track etch dosimeters (TEDs) were also used.

The TEPC, subjectively judged to provide the most accurate estimation of true dose equivalent, was used as the reference for comparison with other devices. At a position of 81 cm from the plutonium fluoride source, the TEPC measured dose equivalent was 14.5 ± 0.8 (6%) mrem/h for eight measurements; the average of the TEPC, multisphere, and ^{3}He spectrometer measurements was 14.5 ± 2.0 (14%) mrem/h. At 81 cm from the plutonium-beryllium source at the D-mm position, the TEPC measurements averaged 41.8 ± 1.5 (4%) mrem/h; all of the devices averaged 39.4 ± 4.4 (11%) mrem/h. Also, at 81 cm from the

plutonium-beryllium source at the 150-mm position in the heavy water, the TEPC measured 8.23 ± 0.5 (6%) mrem/h; all the devices averaged 8.5 ± 0.6 (7%) mrem/h. The uncertainties represent one standard deviation in the measured values.

In view of the many possible errors, the agreement among the various measurements is excellent. The TEPC, multisphere spectrometer, and ^{3}He spectrometer are self-calibrating and derive dose equivalent from first principles; they do not rely on a common calibration. The close agreement between completely different methods gives credibility to the accuracy of the measurements. It is believed that the dose equivalent measurements on the plutonium fluoride source are accurate within about ±15%.

After the dose equivalent rates and neutron energy spectra had been measured at specific work locations, passive dosimeters including the thermoluminescent neutron dosimeter (TLND) and TEDs were positioned on water phantoms at the same approximate locations. Often the measurements were made in nonuniform fields, but this was necessary because of the lack of time to make repetitive measurements at exactly the same location. At most positions along the plutonium production lines and storage areas, the various instruments agreed within 30%. Surprisingly, the TLND also agreed within about 30%, except for a few locations. The TLND gave poor agreement at locations where the neutron energy spectra were markedly different from that of the plutonium-fluoride calibration source. These included the K-Reactor shield door, where the TLND overestimated the dose equivalent by a factor of 3 because of the large number of low-energy neutrons present, and the Cf shipping cask, where neutron absorbers removed most of the lower energy neutrons, so that the TLND estimated the dose equivalent to be 0.3 times the value measured by other devices.

Based on the measurements made, it is recommended that the SRP investigate using a combination dosimeter to more accurately assess dose equivalent in situations where the neutron energy spectrum is very different from the calibration source. The combination dosimeter includes a TLD-albedo dosimeter component to measure lower-energy neutrons (the TLD-albedo response per unit of dose equivalent is almost constant below about 10 keV) and a TED component to measure high energy neutrons above about 100 keV. If neutron quality factors are increased in the future, some SRP workers may be limited by neutron exposure. It is also recommended that SRP investigate using alarming personnel monitors, such as the neutron sensitive pocket rem meter or total dose meter to provide an immediate indication of the accumulated dose equivalent.

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1.0 INTRODUCTION

Neutron dosimetry is of increasing importance because of concerns about low-level radiation health effects and about neutrons producing a greater degree of biological damage than previously thought. These concerns led the International Commission on Radiological Protection (ICRP) to recommend increasing quality factors to a value of 20 for fast neutrons (ICRP 1985). The ICRP recommendation will impact operations at all U.S. Department of Energy (DOE) facilities where plutonium, californium, and other neutron sources are handled, but specifically will impact the Savannah River Plant (SRP), which produces more low-exposure plutonium, more ^{238}Pu for isotopic heat sources, and more californium than any other DOE plant. Because of these operations, some SRP workers have a high potential for significant neutron exposure. The adoption of a quality factor value of 20 for neutrons would restrict or limit the operations of these workers.

As a result of these concerns about the accuracy of neutron dosimetry and impending changes in neutron quality factors, SRP contracted with Pacific Northwest Laboratory (PNL)(a) to make neutron dose and spectrum measurements at typical work locations and the calibration facility at SRP. The measurements were intended to assess the adequacy of the existing neutron dosimetry. They were conducted in October 1985 and April 1986, and included neutron energy spectrum measurements; dose and dose equivalent measurements at locations where TLD-albedo dosimeters were exposed; and tissue equivalent proportional counter (TEPC) measurements to obtain event size distributions, from which quality factors could be obtained.

Three different types of neutron energy spectrometers were used in the neutron energy spectrum measurements. The Bonner sphere or multisphere spectrometer (Bramblett, Ewing, and Bonner 1960), the spectrometer most often used by health physicists, was used because it responds over a wide range of energies from thermal to over 20 MeV. However, the mathematical technique used to unfold the energy spectra does not give a mathematically unique solution and

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(a) Operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO-1830.

the spectrometer has poor resolution, especially in the intermediate energy range below 10 keV, where the TLD-albedo dosimeter is most sensitive. The NE-213 liquid scintillator spectrometer was also used to measure fast-neutron spectra above about 1.2 MeV. The ^{3}He proportional counter spectrometer was used to measure the neutron flux in the energy range of thermal to 5 MeV.

Dose equivalent rates were measured at many locations by using a combination of methods, including tissue equivalent proportional counters (TEPCs), multisphere spectrometers, and calibrated neutron survey instruments provided by SRP. The TEPC measurements were especially important because they provided not only an absolute measurement of absorbed neutron dose, but also energy deposition spectra from which neutron quality factors could be determined.

Field measurements were also made using the SRP TLD-albedo dosimeters and new CR-39 track etch dosimeters (TEDs) supplied by PNL, Lawrence Livermore National Laboratory (LLNL), and a commercial vendor to field-test their suitability (Parkhurst 1986). These dosimeters were exposed at typical work locations where the dose equivalent rate had been previously measured by the instruments described above.

In the past, neutron exposures were usually small and considered secondary to photon exposures. Consequently, neutron dosimetry tended to be conservative; maximal quality factors of 10 were often used. In general, neutron dosimetry was not very accurate. With increased emphasis on ALARA practices, however, and the expected increase in quality factors by DOE, the accuracy of neutron dosimetry must be increased.

Accurate neutron dosimetry is not easily accomplished because, in general, neutrons are electrically neutral, and we can only indirectly observe the nuclear reactions they produce that produce dose by ionization. Accurate neutron dosimetry is also difficult because of the wide range of energies that must be measured and the variations in linear energy transfer (LET) from neutron-induced secondaries.

The ideal neutron dosimeter has a response per dose equivalent that is uniform for neutrons of all energies. However, all existing survey instruments and personnel neutron dosimeters are highly energy dependent. In spite of claims by manufacturers of accuracy ±15% over an energy range of thermal to 20 MeV, independent measurements (Cosack and Lesiecki 1981), made by exposing commercially available survey instruments to monoenergetic neutrons produced by accelerators, have shown that survey instruments can have serious errors. They can overestimate dose equivalent by a factor of 3 to 4 at energies around 10 keV and underestimate dose equivalent by a factor of 3 at energies around 14 MeV or higher. Because of the energy dependence of the personnel dosimeters and survey instruments, the neutron energy spectrum in which TLD-albedo dosimeters and moderator based instruments are used must be characterized to ensure the accuracy of the dosimetry.

The energy dependence of TLD-albedo dosimeters is well known (Alsmiller and Barish 1974; Brackenbush et al. 1980). A typical TLD-albedo dosimeter has a response per unit energy that can vary by a factor of 20. The Hoy TLD-albedo dosimeter used at the SRP (Korba and Hoy 1969; Hoy 1972) is one of the best TLD-albedo neutron dosimeters available. This design used a 5.1-cm (2-in.) diameter polyethylene hemisphere worn on a belt and held tightly against the body. The Hoy design has excellent sensitivity (it can detect as little as 5 mrem of fast neutrons) and less angular dependence than other TLD-albedo dosimeters. The SRP dosimeter also has better measurement precision than other designs and is capable of giving accurate results if calibrated correctly. Nevertheless, the SRP TLD-albedo neutron dosimeter is highly energy dependent (Piesch and Burgkhardt 1978). The SRP dosimeter must be carefully calibrated and interpreted to give accurate neutron dose results in work situations. Because of the large response for low-energy neutrons below about 10 keV, the TLD-albedo neutron dosimeter is highly sensitive to the effects of room scatter. In some instances for shielded sources, the response of the TLD-albedo dosimeter can be more dependent upon scattered radiation than upon neutrons coming directly from the source.

Chapter 2 describes in detail the equipment used to perform the measurements and its limitations. The work locations and facilities surveyed are described in Chapter 3. The results obtained from the SRP study are discussed in Chapter 4. Chapter 5 presents conclusions and recommendations.

2.0 INSTRUMENTATION

This section describes the method of data analysis and instruments used for this study, including the TEPC, the multisphere, NE-213, and ^{3}He spectrometers, portable survey instruments, and dosimeters.

2.1 TISSUE EQUIVALENT PROPORTIONAL COUNTER

The TEPC shown in Figure 2.1 is a 5-in.-diameter hollow sphere constructed of Shonka A-150 type tissue-equivalent plastic. The wall thickness of the counter provides charged-particle equilibrium for neutrons up to about 20 MeV. (Tissue equivalent means that the plastic contains the same proportions of hydrogen and nitrogen as muscle tissue. The proportions of carbon and oxygen are reversed relative to tissue, but their neutron interaction cross sections are similar for the neutron energy range of concern.) The sphere is filled with a propane-based tissue-equivalent gas. Neutron interactions in the counter wall produce recoil particles (protons or heavy ions) that, upon traversing the gas-filled chamber, ionize gas atoms. The negative ions and electrons move toward the center collecting electrodes, and the positive ions move toward the counter wall, producing a current. The current produces an electrical pulse, which is amplified, analyzed, and stored in the memory of a multichannel analyzer (MCA).

The pulse height (or event size) of the TEPC is directly proportional to the energy deposited in the gas by ionization. The product of the number of events of a given size times the event size gives the energy deposited for a given event size. Summing this product for all event sizes gives the total energy deposited in a known mass of tissue equivalent gas. This is a direct measure of absorbed dose in a tissue-like medium and is a good measure of the absorbed dose in soft tissue.

The problem is how to determine effective quality factors and dose equivalent. One method is shown in Figure 2.2. Figure 2.2a shows the absorbed dose distribution as a function of the event size from the counter. The event size is the energy deposited in the gas from ionizing events divided by the diameter of the counter. (The lineal energy similarly defined as the energy

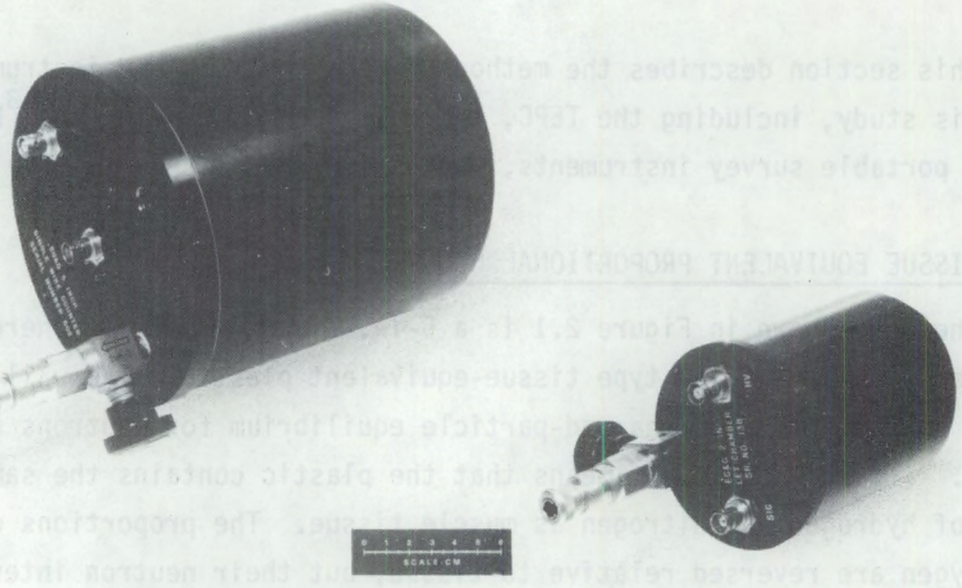


FIGURE 2.1. Tissue Equivalent Proportional Counters

deposited divided by the mean is chord length, which for a sphere is two thirds of the diameter.) Note that photon events and neutron events can be separated by their event size at about 10 keV/µm. One method to convert from event size to LET was developed by H. H. Rossi (1968), and the resulting dose distribution as a function of LET is shown in Figure 2.2b. Because quality factors are defined as a function of LET, it is possible to determine the dose equivalent distribution, shown in Figure 2.2c, as the product of the quality factor, Q(LET), times the absorbed dose, D(LET). The dose equivalent is simply the integral of the distribution shown in Figure 2.2c.

However, there are several problems with this approach. The first is that the Rossi algorithm (Rossi 1968) is not applicable for all neutron energies because it assumes that LET is constant for the charged particle secondaries, completely traversing the counter in straight-line paths. Empirical algorithms for neutron quality factors have been developed to eliminate this problem (Brackenbush et al. 1985).

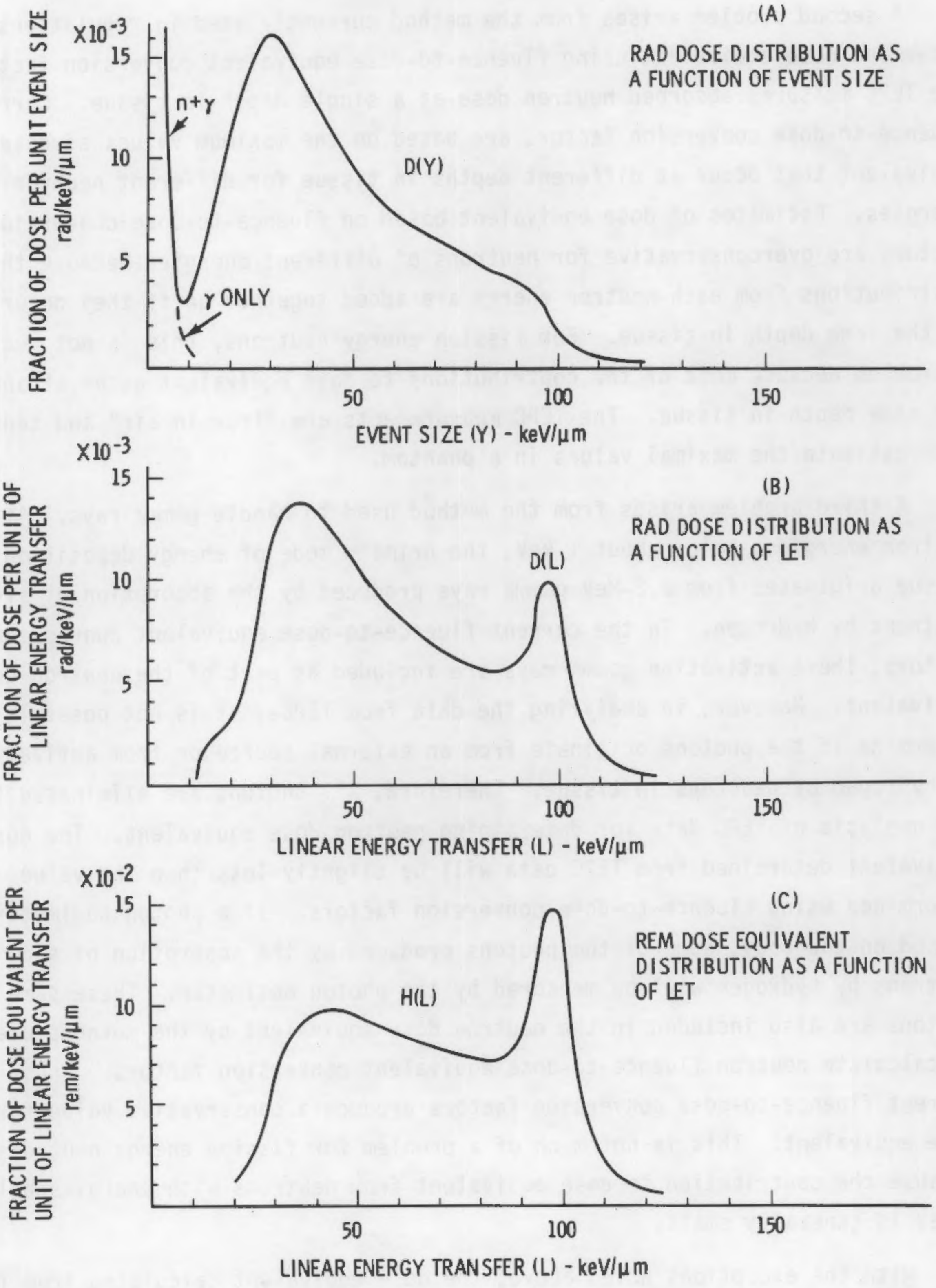


FIGURE 2.2. Dose Distributions from Tissue Equivalent Proportional Counter Data from 1.5-MeV Neutrons

A second problem arises from the method currently used in regulations to determine dose equivalent using fluence-to-dose equivalent conversion factors. The TEPC measures absorbed neutron dose at a single depth in tissue. Current fluence-to-dose conversion factors are based on the maximum values of dose equivalent that occur at different depths in tissue for different neutron energies. Estimates of dose equivalent based on fluence-to-dose conversion factors are overconservative for neutrons of different energies because the contributions from each neutron energy are added together as if they occurred at the same depth in tissue. For fission energy neutrons, this is not much of a problem because most of the contributions to dose equivalent occur at about the same depth in tissue. The TEPC measurements are "free in air" and tend to underestimate the maximal values in a phantom.

A third problem arises from the method used to handle gamma rays. At low neutron energies, below about 1 keV, the primary mode of energy deposition in tissue originates from 2.2-MeV gamma rays produced by the absorption of slow neutrons by hydrogen. In the current fluence-to-dose equivalent conversion factors, these activation gamma rays are included as part of the neutron dose equivalent. However, in analyzing the data from TEPCs, it is not possible to determine if the photons originate from an external source or from activation of hydrogen by neutrons in tissue. Therefore, all photons are eliminated in the analysis of TEPC data for determining neutron dose equivalent. The dose equivalent determined from TEPC data will be slightly less than the value determined using fluence-to-dose conversion factors. If a photon dosimeter is placed on the body, some of the photons produced by the absorption of slow neutrons by hydrogen will be measured by the photon dosimeter. These same photons are also included in the neutron dose equivalent by the methods used to calculate neutron fluence-to-dose equivalent conversion factors. Thus, the current fluence-to-dose conversion factors produce a conservative value for dose equivalent. This is not much of a problem for fission energy neutrons because the contribution to dose equivalent from neutrons with energies below 1 keV is generally small.

With the exceptions noted above, the dose equivalent calculated from TEPC measurements is generally in good agreement with the value calculated from neutron energy spectrum measurements. For most of the energy spectra encountered at SRP, it is expected that the TEPC provided a good measure of neutron dose equivalent. A possible exception is for low energy neutrons, where 2.2-MeV photons from the activation of hydrogen in tissue are a significant contribution to the estimate of dose equivalent. Low-energy neutrons are usually associated with nuclear reactors with massive neutron shields. Low-energy neutrons often result from the multiple scatter and escape of neutrons through penetrations in shields.

2.2 HELIUM-3 SPECTROMETER

The ^{3}He spectrometer is a cylindrical proportional counter 1 or 2.5 in. in diameter and 12-in. long, as shown in Figure 2.3. The tube is filled with a mixture of Ar and ^{3}He. When a neutron with energy below a few MeV interacts with ^{3}He, a proton and triton are liberated with an energy equal to the Q of the reaction (764 keV) plus the energy of the incident neutron. A typical spectrum is shown in Figure 2.4. The probability of a thermal neutron interaction with a ^{3}He atom is thousands of times greater than neutrons with energies in the keV to MeV range. Hence, a "self-calibrating" energy peak occurs at 764 keV (see Figure 2.4).

Although the ^{3}He spectrometer is self-calibrating in determining the energy calibration (keV per channel number), each counter has a slightly different response (number of events per incident neutron) depending on the partial pressures of the ^{3}He and Ar. Therefore, the response of each ^{3}He tube or counter was determined by performing Monte Carlo calculations at various energies from 10 keV to 1 MeV. With each ^{3}He tube's response characterized, its response data were incorporated into the computer code HESTRIP3, which analyzes the spectral data.

To verify the computer code, benchmark measurements were made exposing the ^{3}He spectrometer to the 144-keV beam at the National Bureau of Standards (NBS). Additional measurements were made with the ^{3}He spectrometer exposed to nearly monoenergetic neutrons produced by a Van de Graaff accelerator. The apparatus used has been described previously (Cummings, Endres and Brackenbush 1983). A precision long counter was used to monitor the fast neutron fluence.

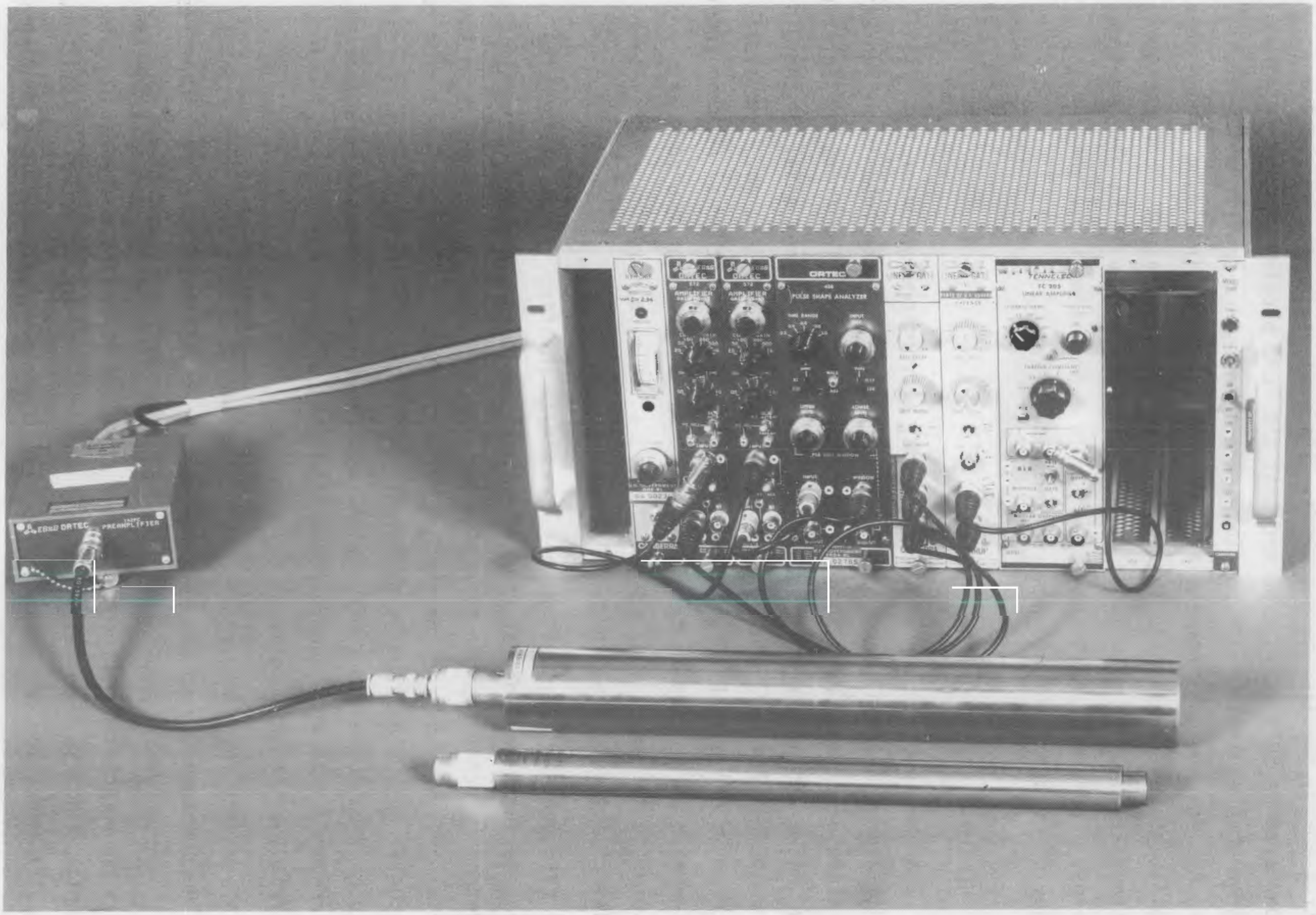


FIGURE 2.3. One- and Two-Inch-Diameter ^{3}He Spectrometers and Associated Electronics

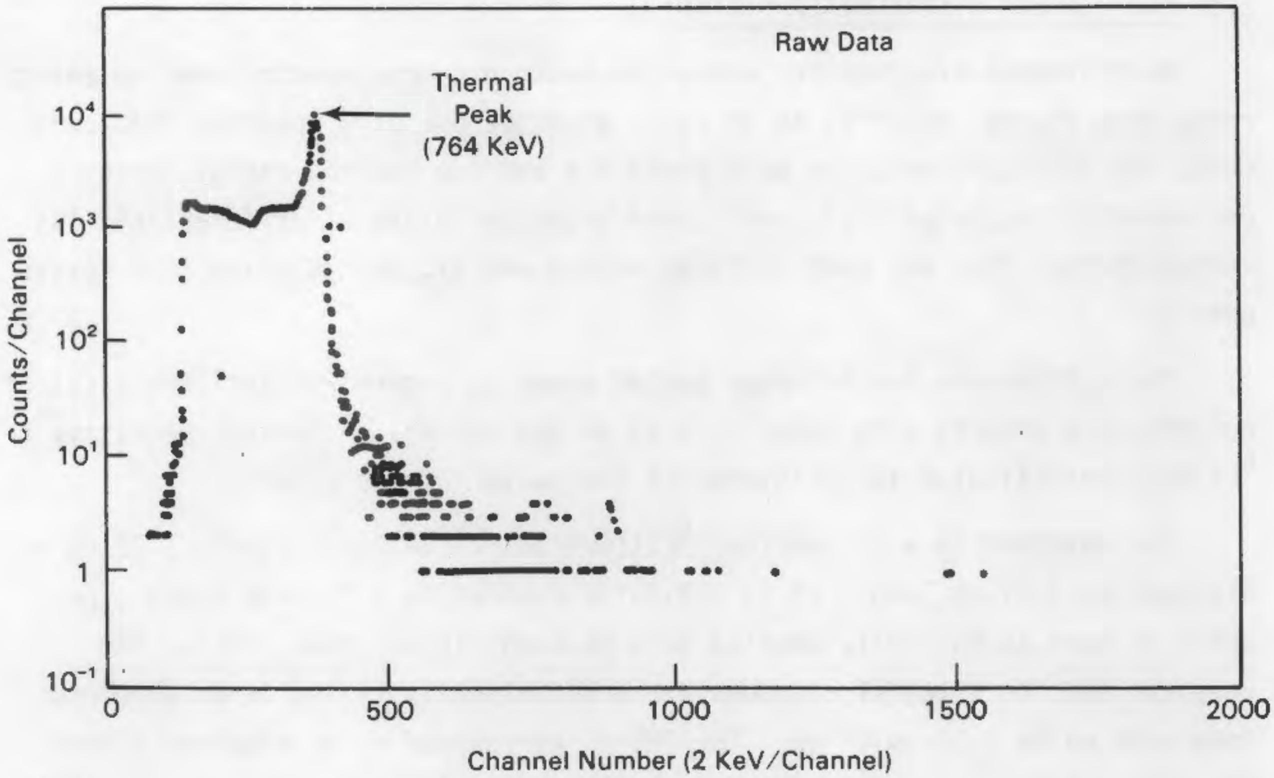


FIGURE 2.4. ^{3}He Spectrometer Input Spectrum

The ^{3}He spectrometer system has a resolution of about 20 keV, making neutrons with energies less than 20 keV difficult to discern from thermal neutrons. Thus, the computed average neutron energy could be in error, particularly in areas with highly degraded spectrum. Nonetheless, neutrons with energies between 20 keV and 1 MeV are accurately measured, and the measured neutron energy spectrum is representative of the actual spectrum.

The ^{3}He spectrometer is ideally suited for determining fluence distributions of neutrons with energies between 20 keV and 1 MeV in energy. However, to meet the objectives of this study the computer code used to analyze the ^{3}He data was revised to account for wall events and recoils caused by neutrons with energies greater than 1 MeV. The computer code HESTRIP4 determines the energy spectra from 50 keV to 5 MeV. The ^{3}He system is used to determine neutron energy spectra, average neutron energy and average quality factor for comparison purposes. A more detailed description is given in Endres et al. (1981) and Brackenbush, Reece and Tanner (1984).

2.3 MULTISPHERE SPECTROMETER SYSTEM

Multispheres are used for measuring neutron energy spectra over an energy range from thermal energies to 20 MeV. With the use of a spectrum unfolding code, the multisphere system will yield the average neutron energy, dose equivalent rate, total flux, kerma, and graphical plots of differential flux versus energy, flux per unit lethargy versus energy, and relative flux versus energy.

The multisphere spectrometer system shown in Figure 2.5 includes a set of polyethylene spheres with holes drilled to the center. A neutron sensitive ^{6}LiI(Eu) scintillator is positioned at the center of the sphere.

The detector is a cylindrical ^{6}LiI(Eu) scintillation crystal, 1.27 cm in diameter by 1.27-cm long. It is optically coupled to a 20.3-cm light pipe, which in turn is optically coupled to a photomultiplier tube (PMT). The detector and its integral components are hermetically sealed in an aluminum tube with walls 0.16-cm thick. The PMT is surrounded by an aluminum sleeve for protection and support for cable connectors. A single cable carries both the high-voltage and output signals, connecting the detector to a preamplifier. The preamplifier decouples the signals and feeds them into the MCA.

Data for the neutron energy spectrum analysis is obtained by taking counts with 1) a bare, unshielded scintillation crystal, 2) the crystal in a Cd shell (0.051 cm thick), and 3) the crystal moderated by spheres of high-density polyethylene (7.6, 12.7, 20.3, 25.5, and 30.5 cm in diameter). The fast-neutron response of this system increases with sphere size because the larger polyethylene spheres moderate the fast neutrons to lower energies where they have a greater probability of being detected by the ^{6}LiI(Eu) scintillator. Cadmium shells placed around the 7.6- and 12.7-cm spheres suppress response to external thermal neutron fields and improve the response of the system to moderated fast neutrons above Cd cutoff (0.4 eV). A stand is used to hold the polyethylene spheres and detector (about 3 ft) above the ground.

The count rate data for the bare detector, the detector covered with Cd and the detector inside the five polyethylene spheres are used as input for the spectral unfolding code SPUNIT (Brackenbush and Scherpelz 1984). Approximate neutron spectra are determined using an iterative unfolding process.

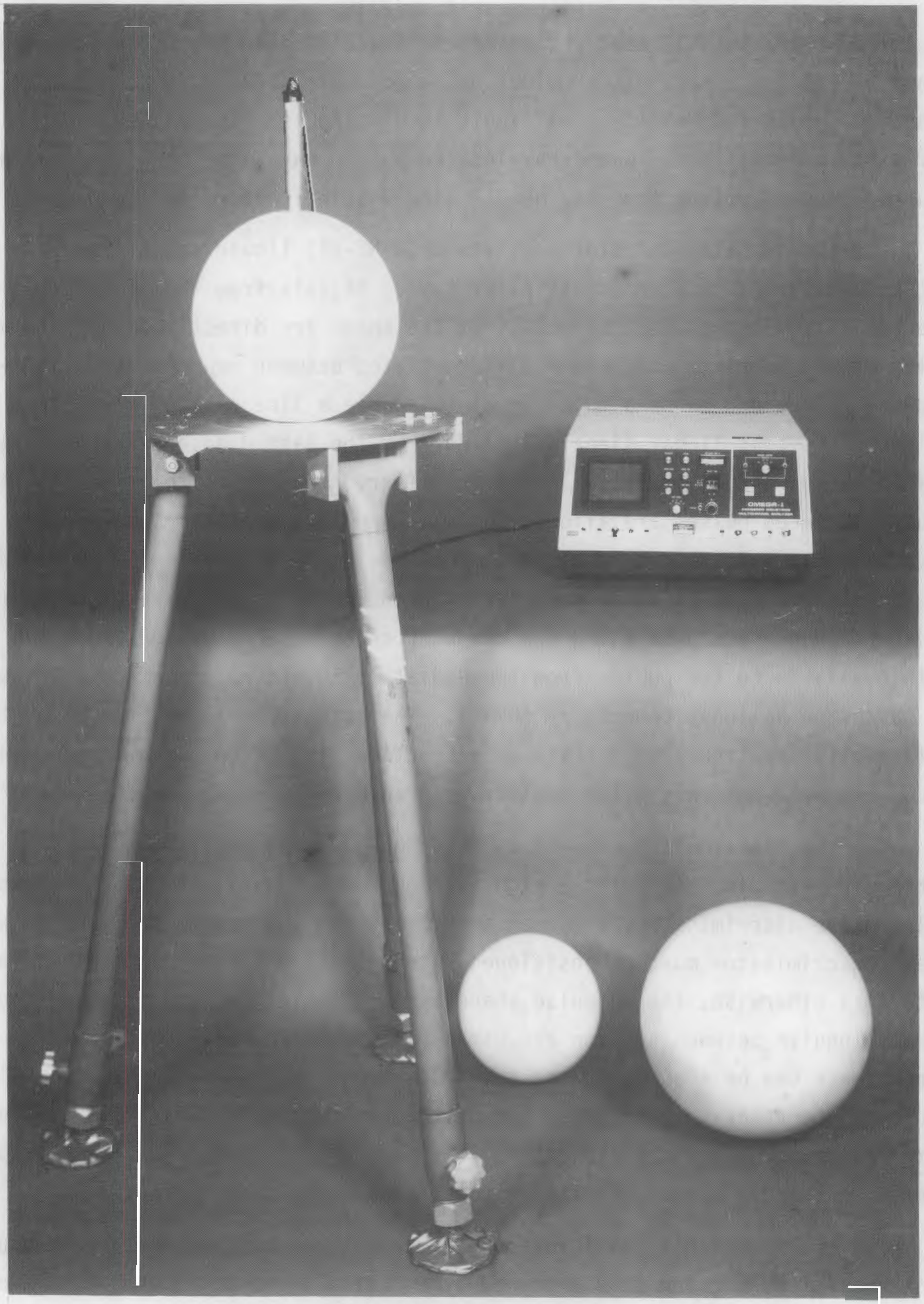


FIGURE 2.5. Multisphere Spectrometer System

2.4 NE-213 SPECTROMETER

The NE-213 scintillator spectrometer is useful over a neutron energy range of 1.2 to 20 MeV. It provides quite accurate spectra at higher energies, but below 1.2 MeV it is difficult to distinguish between neutron and gamma-ray interactions. Gamma-ray-induced pulses have a faster risetime than neutron-induced pulses from the NE-213 liquid scintillator.

The spectrometer detector consists of a NE-213 liquid scintillator optically coupled to a photomultiplier tube. Signals from the photomultiplier are split into two paths. Signals from the anode are directly coupled to a pulse shape discriminator, which differentiates between neutron- and gamma-induced pulses and sends a gate signal to enable a linear gate for neutron pulses. A second linear signal is taken from the last dynode and sent to a scintillation preamplifier, a linear amplifier, and then to the linear gate. Neutron-induced pulses are allowed to pass through the linear gate to be recorded in a multichannel analyzer. The spectral data are then recorded on cassette tape. The data are then transferred in our laboratory to a computer, which processes the data using the computer codes FLYSPEC or FORIST, which are both available to the public from the Radiation Shielding Information Center at Oak Ridge National Laboratory (ORNL). The output of either code gives the differential neutron flux density as a function of neutron energy, and both codes are well documented for quality assurance purposes.

All the electronic equipment for the NE-213 spectrometer can fit into a 6-bin wide NIM Bin, including a high voltage power supply, the Link Systems pulse shape discriminator, a linear amplifier, and a linear gate. The pulse shape discriminator must be positioned within 10 ft of the NE-213 scintillator detector; otherwise, the outpulse shape becomes distorted, and it is difficult to distinguish between neutron and gamma-ray induced pulses. Signals from the linear gate can be transmitted to the multichannel analyzer over a 100-ft-long cable, if necessary. Also, the gain of the photomultiplier is sensitive to temperature changes, so it is desirable to operate the spectrometer in areas where the temperature is constant within a few degrees.

The spectrometer is calibrated before and after neutron spectrum measurements using the Compton edge produced by exposing the spectrometer to a small gamma source.

2.5 SURVEY INSTRUMENTS

Survey instruments were used at each location to measure neutron and gamma dose rates. The survey instruments used in the SRP measurements included:

• Eberline PNR-4 Serial Number 13828	neutron remmeter
• Eberline ESP-1 Serial Number 191	neutron (9 to 3 in.)
• Eberline PNR-4 Serial Number 4303	neutron remmeter
• Victoreen 471	gamma
• Eberline RO-2S Serial Number 302	gamma
• ANDR-50 Snoopy Serial Number 5096	neutron

These instruments provided initial dose rates at each location, which enabled researchers to obtain 1) an accurate estimate of the counting time necessary for reasonable statistics; 2) additional data to estimate the neutron energy by measuring the ratio of the reaction rate from a slow neutron detector at the center of 9- and 3-in. spheres of polyethylene; and 3) additional dose rate information for the overall data base, which was compared with other types of detectors to determine their over-/under-response in the field conditions. The 9-to-3-in. ratio technique consists of determining the thermal neutron flux in a 23-cm-diameter (9-in.) sphere of polyethylene and in a 7.6-cm-diameter (3-in.) Cd-covered sphere of polyethylene using a BF_3 proportional counter and a commercially available survey meter. The effective neutron energy can be determined from the ratio of the responses of the two spheres that are used in Figure 2.6, which are derived from a graph presented by Griffith et al. (1979).

2.6 DOSIMETERS

Dosimeters used for this study were the SRP thermoluminescent-albedo neutron dosimeter (TLND) and three different TEDs supplied by PNL, LLNL, and a commercial vendor.

2.6.1 Thermoluminescent-Albedo Neutron Dosimeter

Figure 2.7 shows the Hoy dosimeter used at the Savannah River Plant (Korba and Hoy 1969; Hoy 1972). This design uses a 5.1-cm-diameter (2-in.-diameter) polyethylene hemisphere to increase its sensitivity, and it can be used to

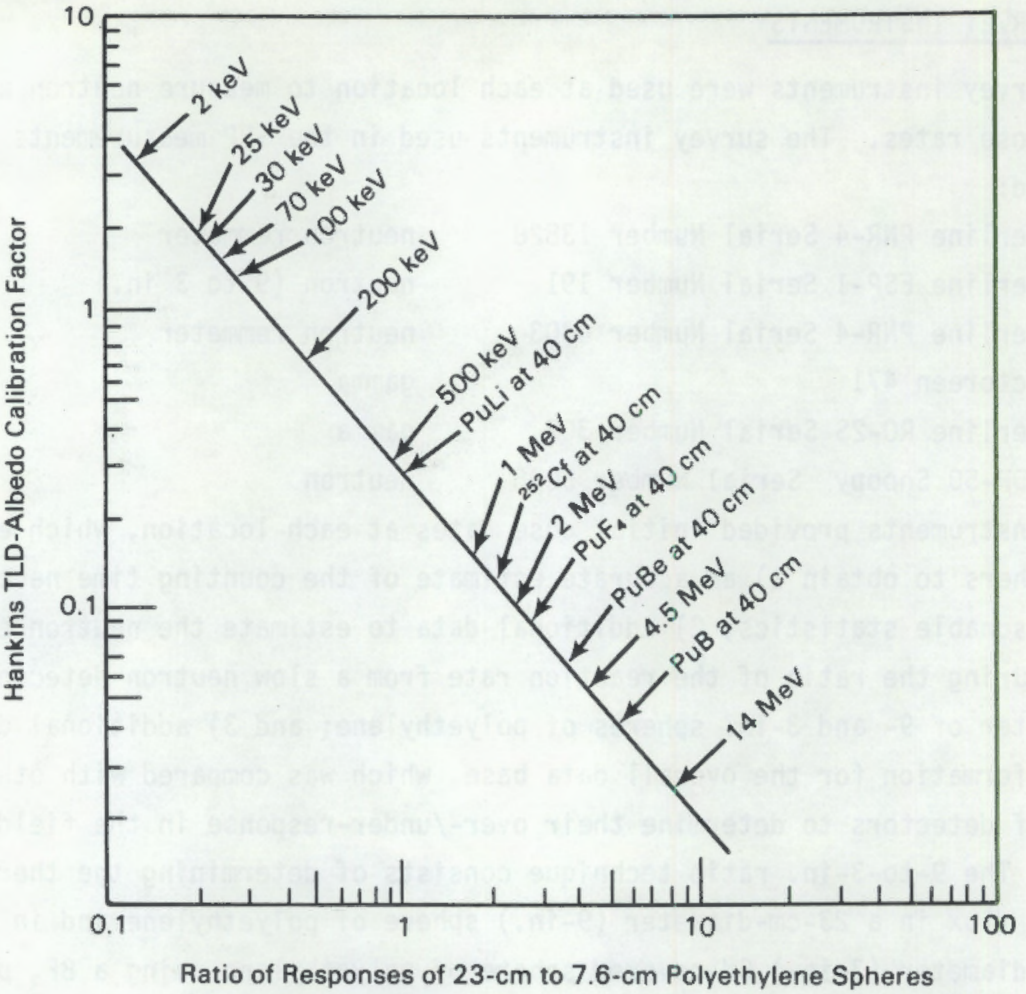


FIGURE 2.6. Effective Neutron Energy as a Function of the Ratio of 23-cm-to-6.7-cm Polyethylene Sphere Responses

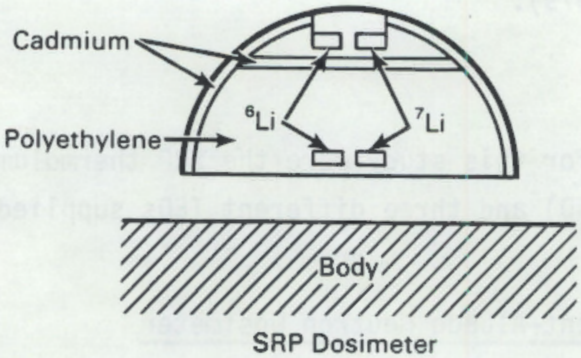


FIGURE 2.7. Schematic Representation of TLND Used at Savannah River Plant

measure as little as 5 mrem of fast neutrons. The Hoy dosimeter is worn close to the body on a belt. It gives high sensitivity, good angular response characteristics, and better precision of measurement than many other designs.

2.6.2 Recoil Track Etch Dosimeters

Neutrons may interact directly in plastic to produce carbon or proton recoils. The charged particles produce damaged areas in the polymer that can be etched out to produce a visible track. Particles with high LET produce a greater degree of damage in the polymer and produce easily observable tracks after etching. However, because of the lower LET hydrogen recoils, the proton tracks are more difficult to observe. Sohrabi (1974) demonstrated that proton recoil tracks could be registered by the electrochemical etching technique introduced by Tommasino (1970). High electric fields at high frequencies cause electrical breakdown at the tips of the tracks, and very vigorous etching occurs (Tommasino and Armellini 1974). The relatively large tracks formed are visible with a microfiche reader or microscope. The technique is sufficiently accurate that one laboratory and a commercial dosimetry service are using this technique with polycarbonate plastic for neutron dosimetry (Griffith, Fisher and Harder 1977; Oswald and Wheeler 1977). Unfortunately, the electrochemical etch technique used on polycarbonate plastic has an energy threshold of about 1.5 MeV. Other materials are being tested in a search for lower energy thresholds (Gammage and Cotter 1977). The polymer poly allyl diglycol carbonate (trade name CR-39®) has an energy threshold below 200 keV and is being used by a commercial laboratory. The dosimeter that uses this material produces tracks from proton recoils. The energy responses of electrochemically etched polycarbonate and CR-39 are shown in Figure 2.8. The CR-39 dosimeter is useful for fast neutron dosimetry.

Neutron recoil track detectors have two major disadvantages, however, they exhibit a background that corresponds from 20 to 60 mrem, depending on the calibration used (Griffith et al. 1979) and they exhibit energy thresholds of about 200 eV for CR-39 and 1.5 MeV for polycarbonate plastic.

The CR-39 polymer was used in the TEDs supplied by PNL and LLNL. Both PNL and LLNL also use electrochemical etching. The TEDs used by PNL are held in place by a plastic holder. This holder measures 8.3-cm long by 3.5-cm wide

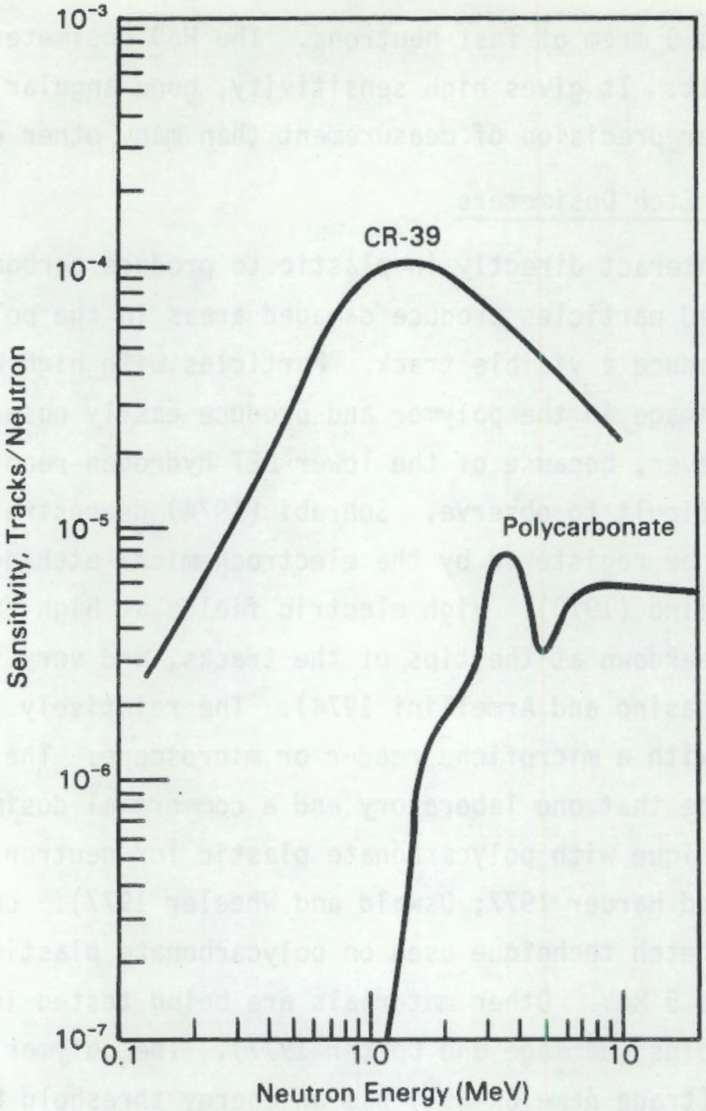


FIGURE 2.8. Measured Neutron Energy Response of Electrochemically Etched Polycarbonate and CR-39 Plastic

and 0.6-cm thick. It can hold up to four TEDs. The TEDs are slipped into the grooved edges of the holder. The LLNL design is a Cd box capable of holding up to three TEDs. The purpose of the Cd shield is to eliminate thermal neutrons and any charged particles that may originate from unwanted sources (e.g., charged particles recoils from neutron interactions in air). The commercially available dosimeter was housed in the SRP TLD badge. It was processed by chemical etching only.

Further details on design, calibration techniques, and response for different neutron dosimeters can be found in the references. All neutron dosimeter irradiations were made using a 6.5-gal water-filled phantom.

3.0 MEASUREMENTS AND RESULTS

This section describes measurements and results at the calibration facility, 736-A Builidng; H-Area B-Line; F-Area B-Line; ^{252}Cf Facility, 773-A Building; and K-Area Reactor. A description of the facility and source are provided for each section along with measurement locations, neutron dose equivalent rates, neutron energy spectra, and response comparisons.

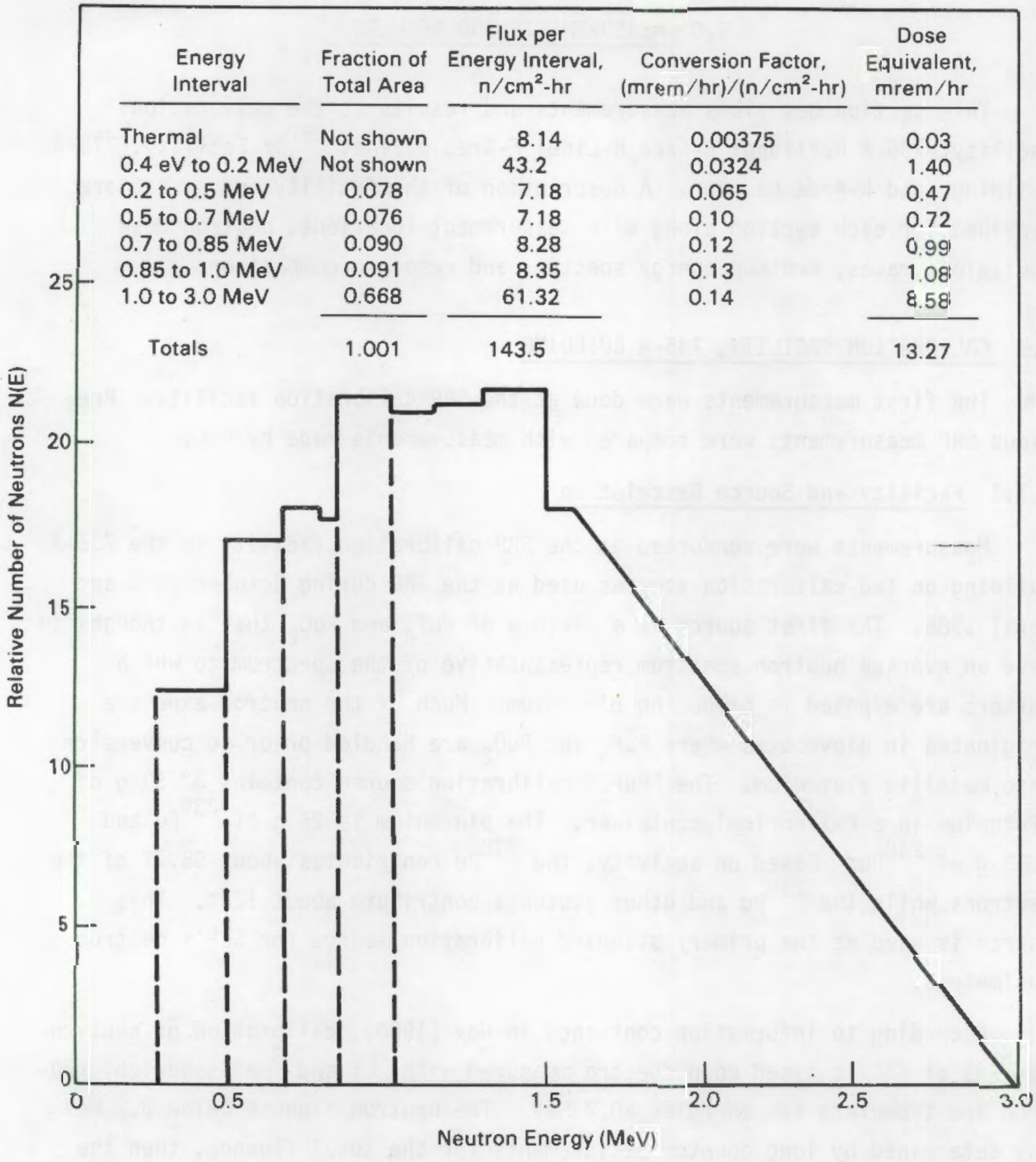
3.1 CALIBRATION FACILITY, 736-A BUILDING

The first measurements were done at the SRP calibration facility. Previous SRP measurements were compared with measurements made by PNL.

3.1.1 Facility and Source Description

Measurements were conducted at the SRP calibration facility in the 736-A Building on two calibration sources used at the SRP during October 1985 and April 1986. The first source is a mixture of PuF_4 and PuO_2 that is thought to have an average neutron spectrum representative of the spectrum to which workers are exposed in producing plutonium. Much of the neutron exposure originates in gloveboxes where PuF_4 and PuO_2 are handled prior to conversion into metallic plutonium. The "PuF_4" calibration source contains 32.53 g of plutonium in a cylindrical container. The plutonium is 25 g of ^{239}Pu and 7.53 g of ^{238}Pu. Based on activity, the ^{238}Pu contributes about 98.7% of the neutrons while the ^{239}Pu and other isotopes contribute about 1.3%. This source is used as the primary standard calibration source for SRP's neutron dosimeters.

According to information contained in Hoy (1980), calibration of neutron sources at SRP is based upon spectra measured with ^{6}Li and ^{3}He "sandwich" neutron spectrometers for energies >0.2 MeV. The neutron fluence below 0.2 MeV was determined by long counter measurements for the total fluence, then the component above 0.2 MeV was subtracted out to arrive at the component below 0.2 MeV. For the PuF_4 source, the SRP calculated dose equivalent rate at 81.3 cm (32 in.) was 13.3 mrem/h based upon the spectrum and flux-to-dose equivalent rate conversion factors shown in Figure 3.1, which is Figure A-4 in



Energy Interval	Fraction of Total Area	Flux per Energy Interval, n/cm^2-hr	Conversion Factor, (mrem/hr)/(n/cm^2-hr)	Dose Equivalent, mrem/hr
Thermal	Not shown	8.14	0.00375	0.03
0.4 eV to 0.2 MeV	Not shown	43.2	0.0324	1.40
0.2 to 0.5 MeV	0.078	7.18	0.065	0.47
0.5 to 0.7 MeV	0.076	7.18	0.10	0.72
0.7 to 0.85 MeV	0.090	8.28	0.12	0.99
0.85 to 1.0 MeV	0.091	8.35	0.13	1.08
1.0 to 3.0 MeV	0.668	61.32	0.14	8.58
Totals	1.001	143.5		13.27

FIGURE 3.1. Spectrum of PuF$_4$ Source in Air at 32 in.

Hoy (1980). At the time of these measurements, the dose equivalent rate was computed to 11.9 mrem/h at the same position, based on the decay of ^{238}Pu.

The second calibration source measured at SRP was a PuBe source housed in a cylindrical tank of D_2O. The source could be moved to the front face of the D_2O tank or to positions further back in the drum that provide greater moderation. For these measurements two source positions were measured: the source at the front face of the D_2O tank (the 0-mm position) and the source 150 mm back into the tank (the 150-mm position). This source is used at SRP to calibrate neutron field survey instruments and as a secondary standard calibration source for dosimeters.

The SRP calculated dose equivalent rate for the 0-mm D_2O position is 34.2 mrem/h. The spectrum and the flux-to-dose equivalent conversion factors used to calculate this value are shown in Figure 3.2, which is reproduced from Figure A-5 of Hoy (1980). The SRP calculated dose equivalent rate for the 150-mm D_2O position is 12.3 mrem/h. The spectrum and conversion factors used to calculate this value are shown in Figure 3.3, which is reproduced from Figure A-6 of Hoy (1980).

3.1.2 Measurement Locations

Two sets of measurements were made by PNL on the PuF_4 calibration source during the measurements conducted in October 1985. The first set was made with the PuF_4 source suspended 30.5 cm (12 in.) above a 23.5-in.-diameter paraffin-filled drum, which is used to store the source. The location of the instruments and the distance from the walls of the room are shown in Figure 3.4. The centers of the detectors, which consisted of the NE-213 spectrometer, the TEPC, and the multisphere spectrometer, were at a distance of 81 cm (32 in.) from the center of the source and 119 cm (97 cm) above the concrete floor. This configuration closely matches the SRP dosimeter irradiations, where the neutron dosimeters are placed on a water-filled phantom at 81 cm (32 in.) from the source. Measurements were also made with the multisphere spectrometer at the position of the TEPC at 81 cm (32 in.) from the center of the source.

A second set of measurements was made with the paraffin drum removed to eliminate the effects of scattering from the paraffin. Measurements were

Energy Interval	Fraction of Total Area	Flux per Energy Interval, n/cm²-hr	Conversion Factor, (mrem/hr)/(n/cm²-hr)	Dose Equivalent, mrem/hr
Thermal	Not shown	2.0	0.00375	0.12
0.4 eV to 0.2 MeV	Not shown	304	0.0324	9.85
0.2 to 0.5 MeV	0.030	5.52	0.068	0.38
0.5 to 1.0 MeV	0.164	30.17	0.122	3.68
1.0 to 2.0 MeV	0.250	46.00	0.137	6.30
2.0 to 5.0 MeV	0.373	68.63	0.129	8.85
>5 MeV	0.183	33.67	0.148	5.98
Totals	1.004	521		34.17

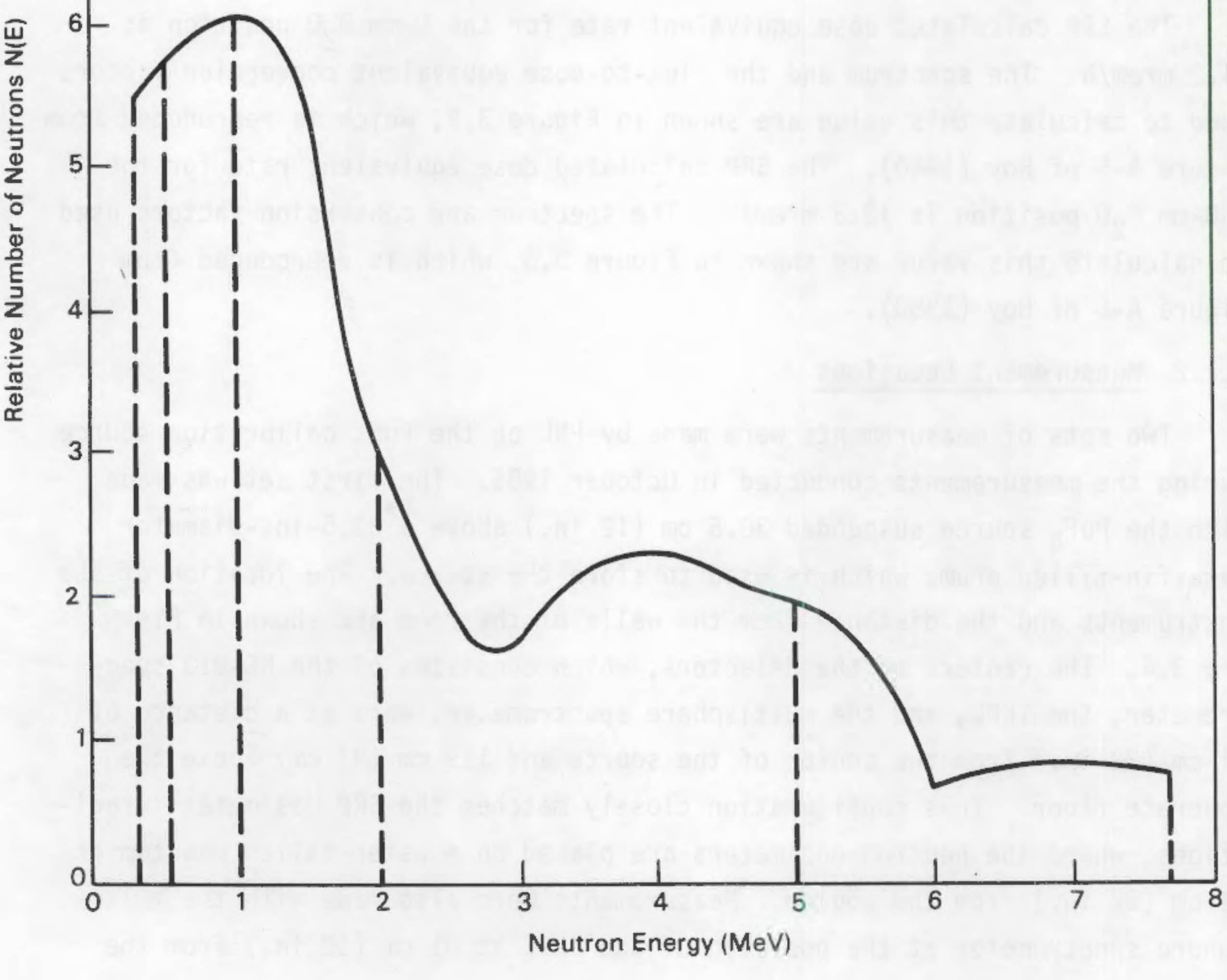
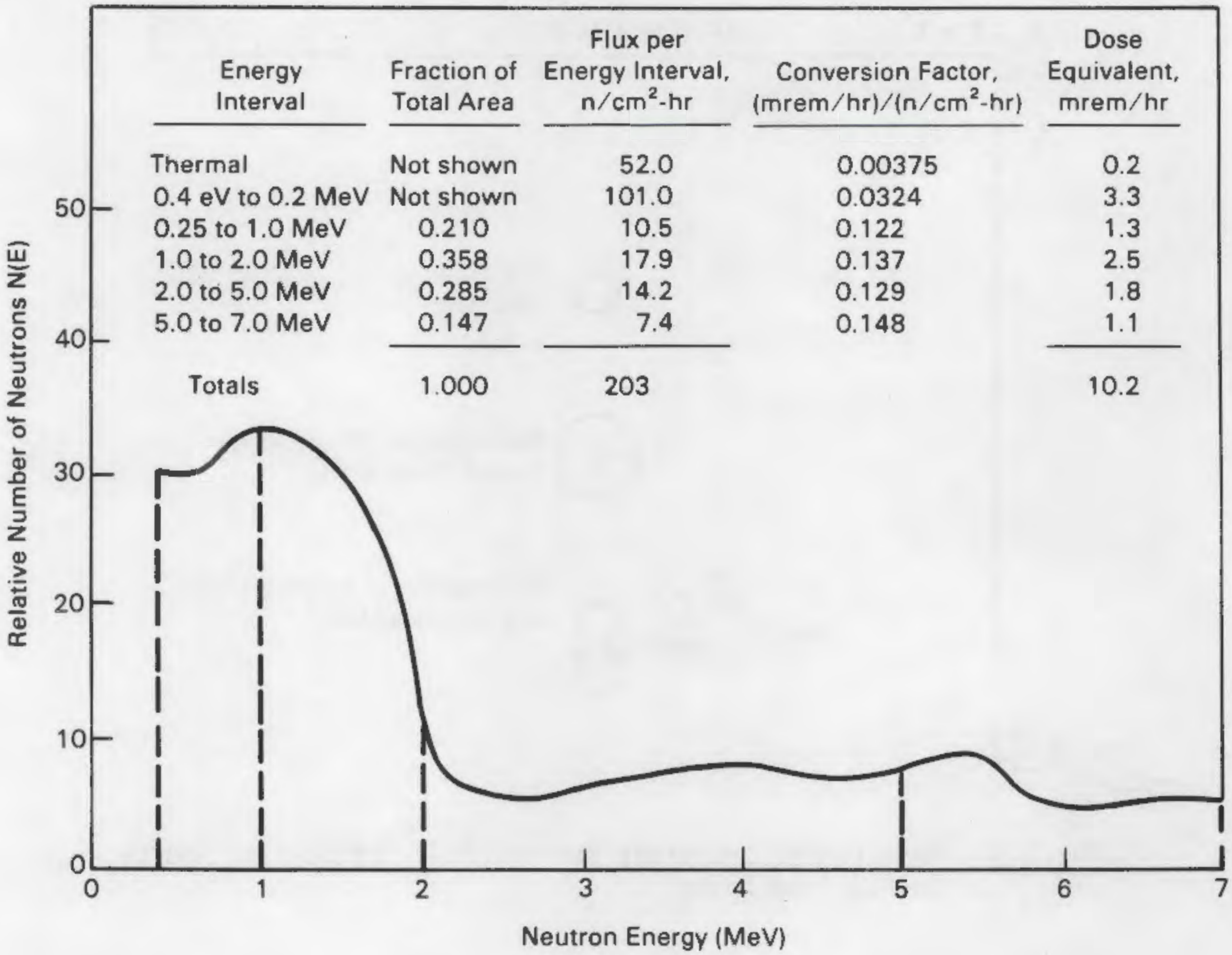


FIGURE 3.2. Spectrum of 10-Ci PuBe Source 32 in. from Face of D_2O at D-mm Depth



Energy Interval	Fraction of Total Area	Flux per Energy Interval, n/cm²-hr	Conversion Factor, (mrem/hr)/(n/cm²-hr)	Dose Equivalent, mrem/hr
Thermal	Not shown	52.0	0.00375	0.2
0.4 eV to 0.2 MeV	Not shown	101.0	0.0324	3.3
0.25 to 1.0 MeV	0.210	10.5	0.122	1.3
1.0 to 2.0 MeV	0.358	17.9	0.137	2.5
2.0 to 5.0 MeV	0.285	14.2	0.129	1.8
5.0 to 7.0 MeV	0.147	7.4	0.148	1.1
Totals	1.000	203		10.2

FIGURE 3.3. Spectrum of 10-Ci PuBe Source 32 in. from Face of D_2O at 150-mm Depth

repeated with the multisphere spectrometer at 81 cm away from the source, and a second set of measurements was made with the TEPCs and a ^{3}He spectrometer containing a 2.5-in.-diameter ^{3}He proportional counter.

While measurements were being made in one room with the PuF_4 source, a second set of measurements was being made simultaneously with a PuBe source in another room. The experimental arrangement for the PuBe measurements are shown in Figure 3.5. The nominal 10-Ci PuBe source is housed in a tank of heavy water (D_2O) and can be positioned at various distances into the D_2O drum to provide different neutron energy spectra. Measurements were made with the PuBe source in contact with the surface (the 0-mm D_2O position) and at a depth of

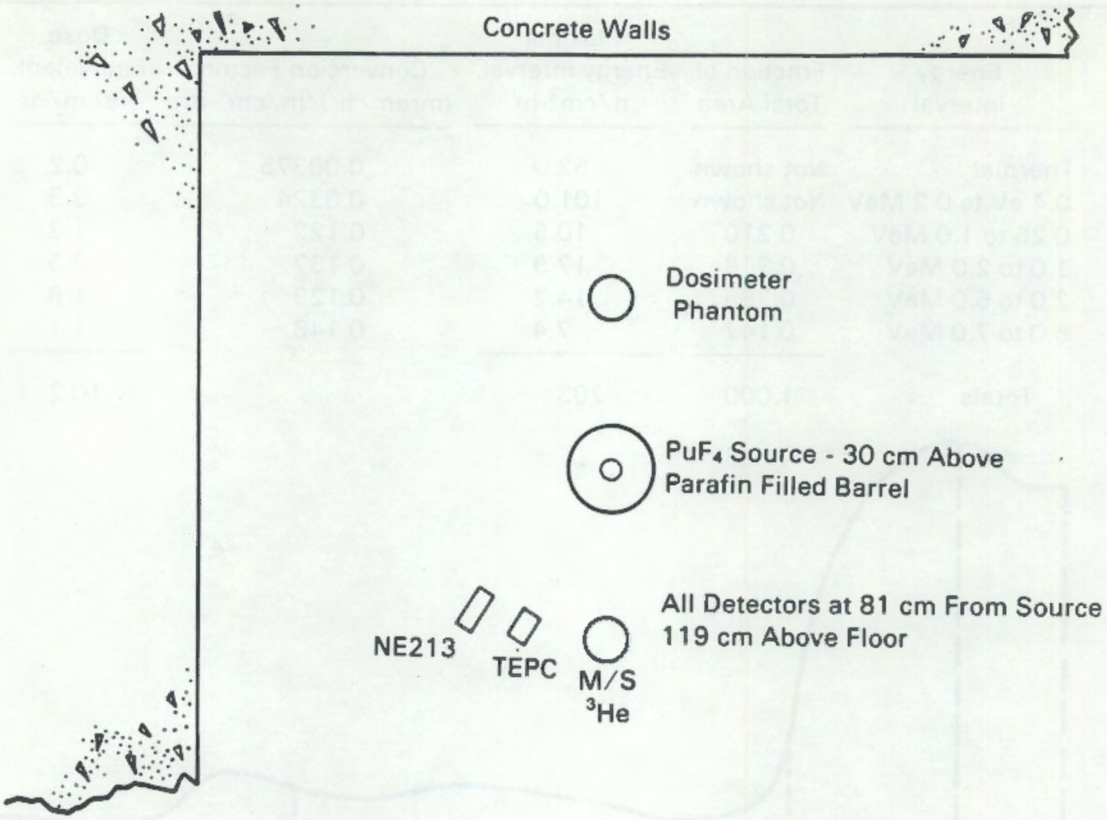


FIGURE 3.4. Measurement Locations for the PuF_4 Calibration Source in 736-A Building

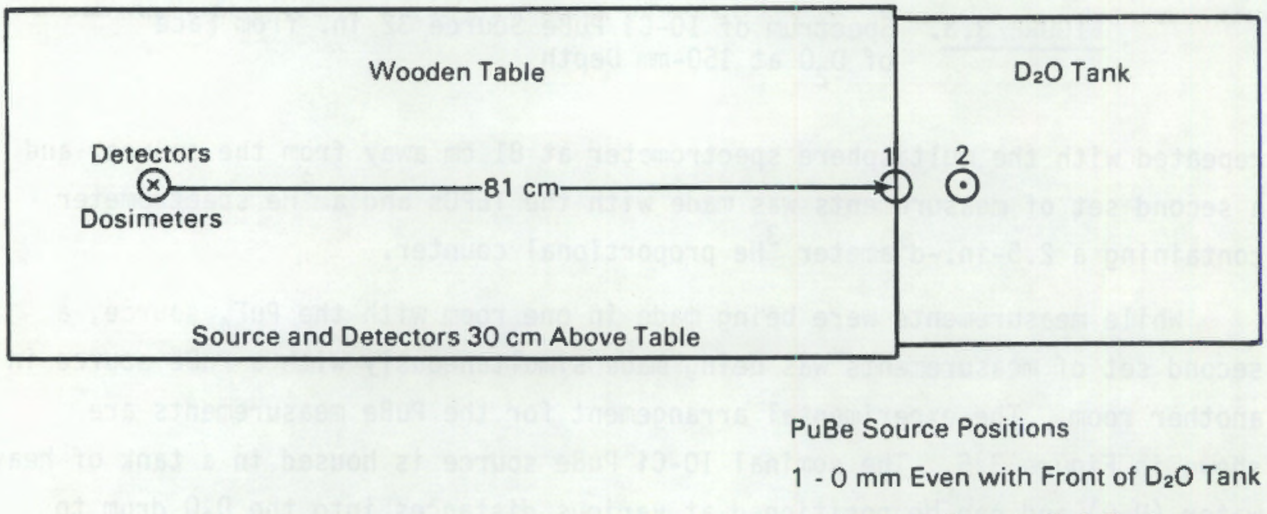


FIGURE 3.5. Measurement Locations for the PuBe Calibration Source in 736-A Building

150 mm into the drum (the 150-mm D_2O position). Because of the anisotropy of the neutron field, only one dosimeter or spectrometer measurement could be made at a time. The detectors were positioned at 81 cm from the front face of the D_2O drum at 30 cm above the support table.

A second set of measurements was conducted in the calibration facility during April 1986. These measurements were performed in an effort to obtain the most accurate data possible on the two calibration sources since it was felt that the measurements were the most critical. During April, measurements were conducted using three different TEPCs and the NE-213 spectrometer. The measurement locations were identical to the locations selected during the measurements conducted in October 1985. Again, measurements were performed on the PuF_4 source both with and without the paraffin drum.

After the April measurements, the data collected during both sets of measurements (October 1985 and April 1986) were carefully analyzed and evaluated. Two TEPCs (Numbers 501 and 1173) demonstrated the best resolution and reproducibility. Both of these TEPCs were checked with an NBS-traceable ^{252}Cf source at PNL and had measured the neutron dose equivalent rate within 5% of the computed value based on the neutron emission rate provided by NBS. Therefore, the measurements conducted at SRP during October 1985 and April 1986 with these two TEPCs were used to determine the neutron dose equivalent rates of the PuBe and PuF_4 calibration sources. Three measurements of the PuBe source at each position were used to compute a neutron dose equivalent rate while five measurements of the PuF_4 were used. An average neutron dose equivalent rate was computed for each source with a standard deviation calculated. For the PuF_4 source, measurements with and without the paraffin drum were computed together since no appreciable differences was measured by the TEPC for either configuration. The PuBe source was measured to have a neutron dose equivalent rate of 41.8 ± 1.5 mrem/h at the 0-mm position and 8.23 ± 0.05 mrem/h at the 150-mm position. The PuF_4 source was measured to have a value of 14.5 ± 0.8 mrem/h.

3.1.3 Neutron Dose Equivalent Rates

Neutron dose equivalent rate measurements were performed for the two sources in the calibration facility of 736-A Building. The PuF_4 source was measured at a distance of 81 cm with and without the drum in place. The PuBe source was measured at a distance of 81 cm from the front edge of the D_2O cylinder. The PuBe source was measured while in two positions. One position had the source even with the front edge and the other position had the source back from the front edge a distance of 15 cm. Table 3.1 give the results of the neutron dose equivalent measurements as measured by the TEPC, M/S, ^{3}He, remball, and dosimeters.

The agreement between the TEPC, M/S, ^{3}He, and TEDs from PNL and LLNL was excellent for all four source configurations. The commercial TED and the dosimeters used at SRP (the TLNDs) responded low compared with the TEPC. Section 3.1.5 describes these comparisons in more detail.

TABLE 3.1. Neutron Dose Equivalent Rates (mrem/h) in the Calibration Facility of 736-A Building

Source	Calculated	TEPC	^{3}He	M/S	Remball (PNR-4)	PNL TED	LLNL TED	Commercial TED	TLND
PuF_4 with drum	-	14.5	-	12.7	16.2	12.7(a)	16.4	4.4	9.3
PuF_4 without drum	11.9	14.5	15.2	12.6	16.0	17.8	16.7	4.7	9.5
PuBe, 0 mm	34.2	41.8	38.8	34.4	46.6	41.2	35.8	28.6	32.0
PuBe, 150 mm	12.3	8.2	8.5	8.1	10.7	7.3	6.7	4.7	13.0

(a) Denotes 12.7 mrem/h based on average of two separate CR-39 exposures at 10.3 and 15.0 mrem/h.

3.1.4 Neutron Energy Spectra

Three different instruments were used to measure the neutron energy spectra: the lithium iodide detectors with polyethylene spheres or multisphere system (M/S), the ^{3}He proportional counter and the NE-213 liquid scintillator. The M/S determines neutron energy spectra from thermals to 20 MeV. The ^{3}He spectrometer determines energy spectrum from thermal to ~5 MeV, while the NE-213 measures neutron energies >1.2 MeV. Since the neutron energy spectra contained significant amounts of neutrons below 1.2 MeV, the neutron energy spectra computed by the NE-213 was used for comparison purposes only. The NE-213 systems with the computer code FLYSPEC yielded neutron flux plots above 1.2 MeV. However, the data acquired by the M/S system and ^{3}He spectrometer used with the unfolding codes SPUNIT and HESTRIP4, respectively, provided reasonable computation of the entire energy spectra at all locations.

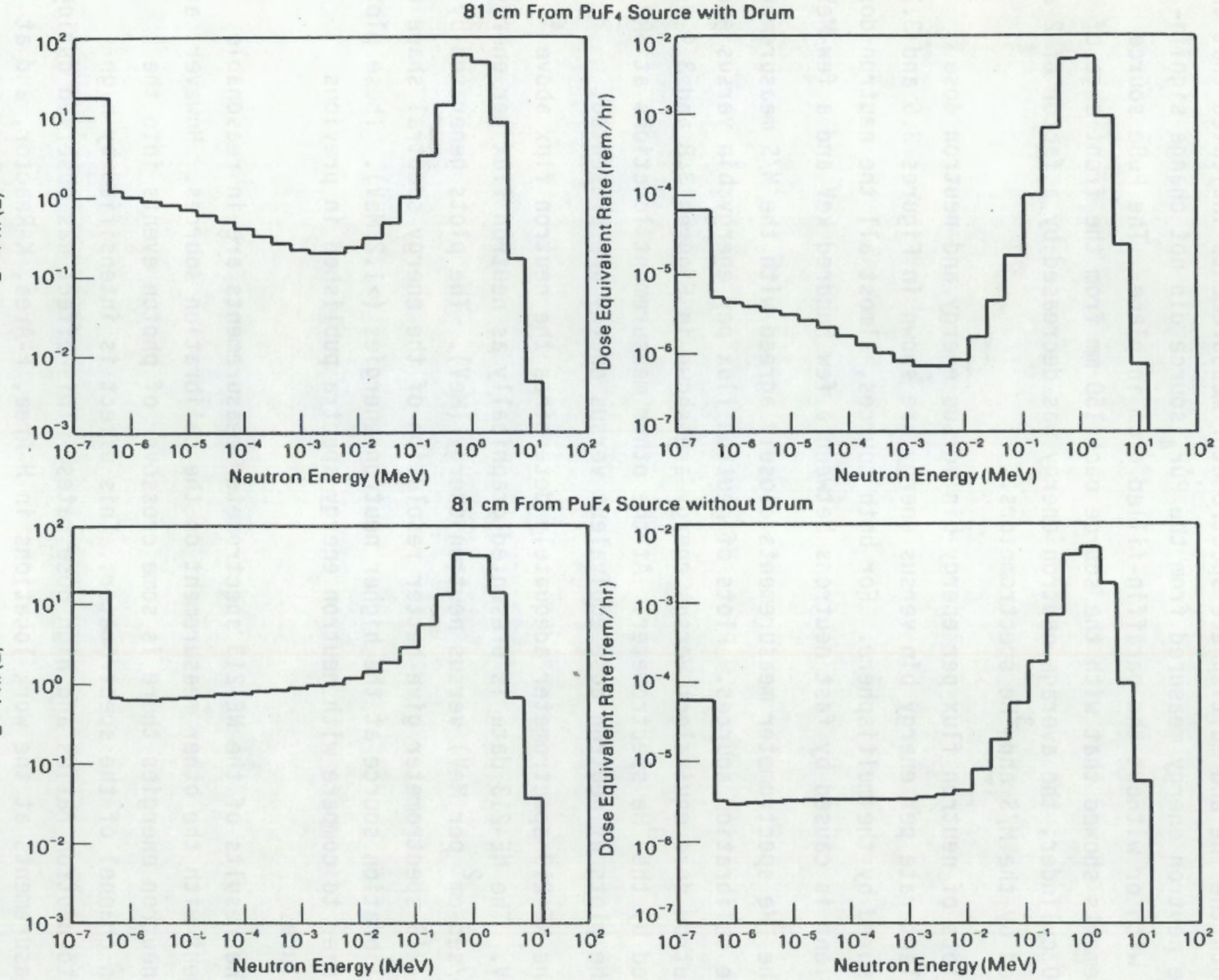
Both the ^{3}He and multisphere spectrometer measurements indicated that the average neutron energy measured from the PuF_4 source did not change significantly with or without the paraffin-filled drum in place. The PuBe source measurements showed that with the source back 150 mm from the front edge of the D_2O cylinder, the average neutron energy was decreased by a factor of 2 as measured by the M/S and ^{3}He spectrometers.

Plots of neutron flux per energy bin versus energy and neutron dose equivalent rate per energy bin versus energy are shown in Figures 3.6 and 3.7, as measured by the multisphere. For both sources, almost all the neutron dose equivalent is caused by fast neutrons between a few hundred keV and a few MeV.

The ^{3}He spectrometer measurements closely agreed with the M/S measurements for the calibration sources. Plots of neutron flux per energy bin versus energy and neutron dose equivalent versus energy are shown in Figures 3.8 and 3.9 as measured by the ^{3}He spectrometer. At the other measurement locations at SRP only the plots of neutron dose equivalent versus energy are presented.

The NE-213 spectrometer adequately determines the neutron flux above 1.2 MeV. The NE-213 data is presented graphically as neutron flux per energy bin (n/sec-cm^2 per MeV) versus neutron energy (MeV). The plots generated by the NE-213 spectrometer give better resolution of the energy spectral shape of the calibration source at the higher neutron energies (>1.2 MeV). These plots are easier to compare with neutron energy spectra published in previous literature.

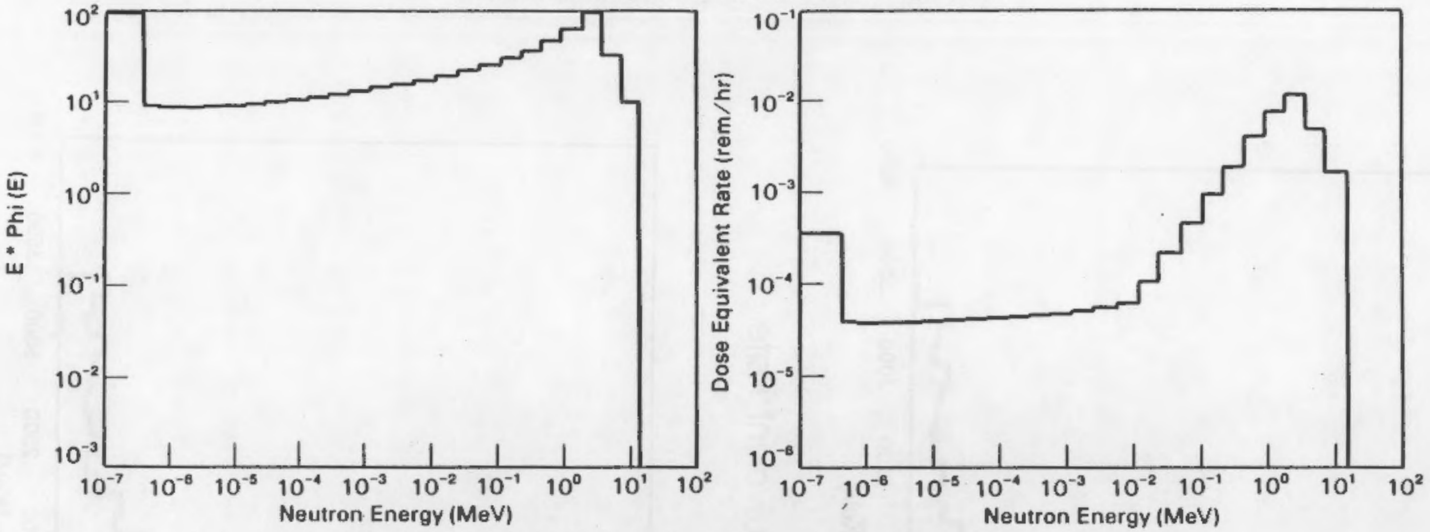
The results of the NE-213 spectrometer measurements are in reasonable agreement with the other measurement on the calibration sources. However, at lower neutron energies there is some crossover of photon events into the neutron channel of the spectrometer. This effect is intensified by high gamma-to-neutron ratios and high dose rates. This effect was observed during the measurements at the work locations in H-Area, F-Area, K-Reactor, and at the CF-252 Facility in 773-A Building. Therefore, no plots of the neutron energy spectra measured by the NE-213 are provided at any measurement location other than the calibration facility.


81 cm From PuF₄ Source with Drum

81 cm From PuF₄ Source without Drum

FIGURE 3.6. Neutron Energy Spectra of PuF_4 Source as Measured by the Multisphere Spectrometer

81 cm From PuBe Source at 0 mm in D_2O Tank



81 cm From PuBe Source at 150 mm in D_2O Tank

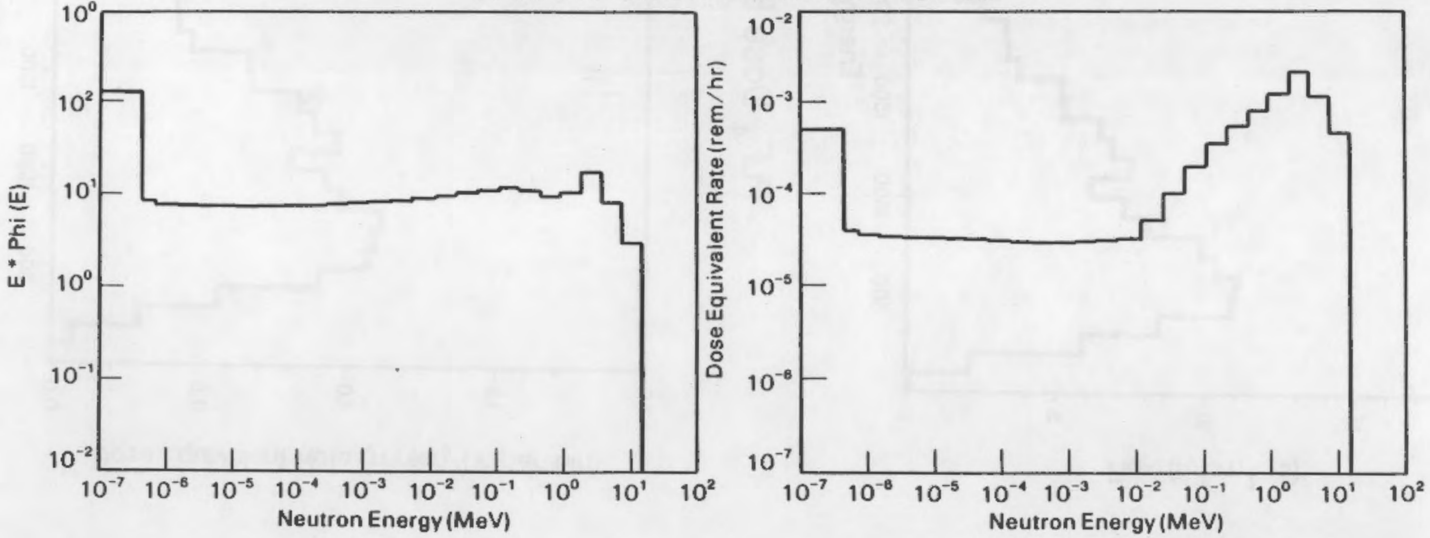
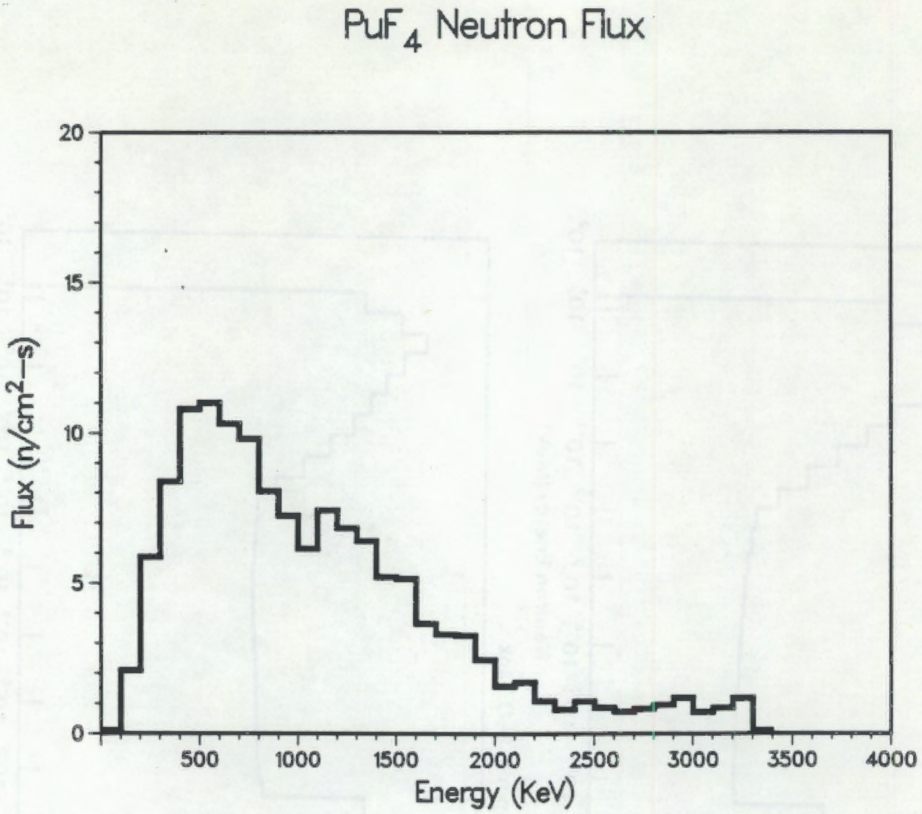
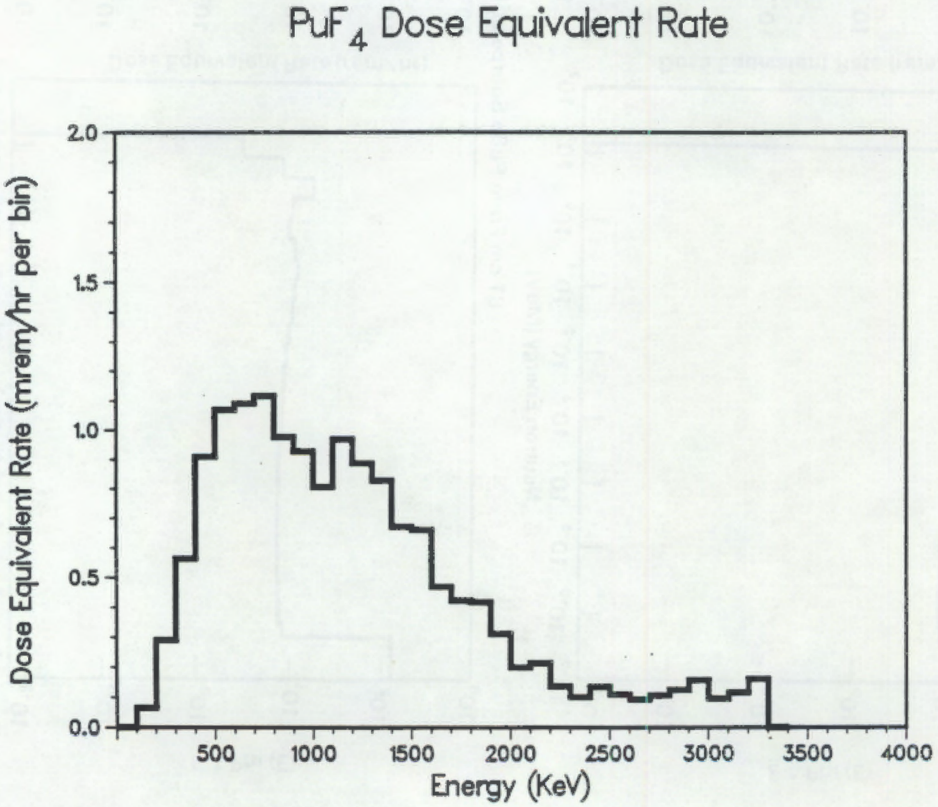


FIGURE 3.7. Neutron Energy Spectra of PuBe Source as Measured by the Multisphere Spectrometer



PuF$_4$ Neutron Flux



PuF$_4$ Dose Equivalent Rate

FIGURE 3.8. Neutron Energy Spectra of the PuF$_4$ Source as Measured by the ^{3}He Spectrometer

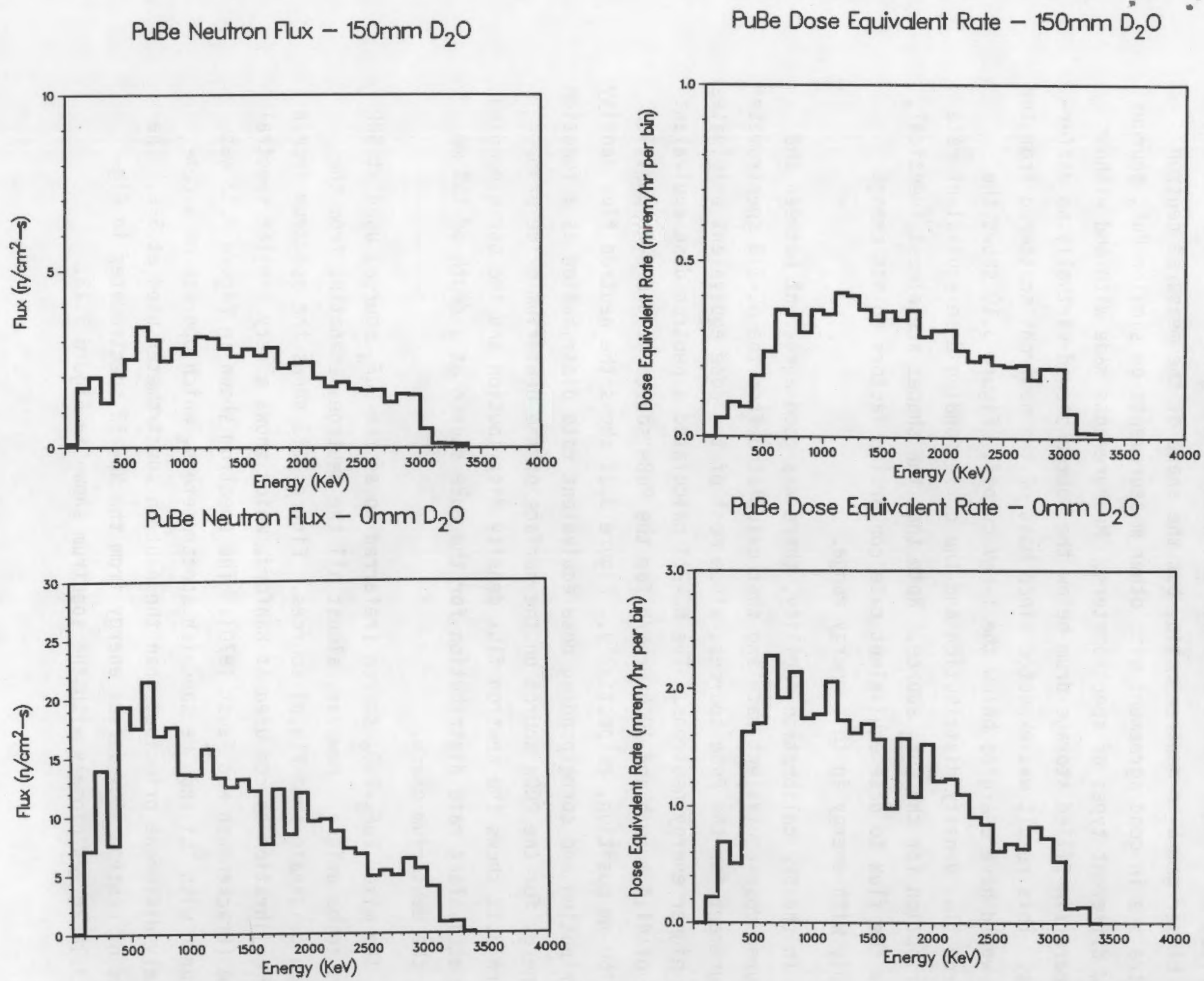


FIGURE 3.9. Neutron Energy Spectra of the PuBe Source as Measured by the ^{3}He Spectrometer

The PuF_4 neutron source measurements with the NE-213 spectrometer exhibited more gamma crossover since the neutron energies are lower and there is a higher gamma-to-neutron ratio, but the shape of the measured neutron spectra are in good agreement with other measurements on similar PuF_4 sources using different types of spectrometers. Measurements made with and without the paraffin-filled storage drum below the source showed virtually no differences. This result was expected since most of the neutrons scattered from the drum would have energies below the 1-MeV cutoff. Figure 3.10 shows the neutron flux density distribution and the corresponding dose equivalent rate distribution for the PuF_4 source. Note that the shapes are almost identical, since the flux to dose equivalent rate conversion factors do not change rapidly with energy in this energy range.

In the SRP calibration facility, there was good agreement between the measured dose-equivalent rate and that calculated from the NE-213 spectrometer measurement for the PuBe sources, since most of the dose equivalent originates from higher energy neutrons. The NE-213 calculated a neutron dose equivalent rate of 44.4 mrem/h and 10.6 mrem/h for the PuBe source at the 0-mm position and 150-mm position, respectively. Figure 3.11 shows the neutron flux density distribution and corresponding dose equivalent rate distribution as a function of energy for the PuBe source on the surface of the deuterium oxide drum. Figure 3.12 shows the neutron flux density distribution and the corresponding dose equivalent rate distribution for the PuBe source at a depth of 150 mm into the deuterium oxide.

The mixed PuF_4-PuO_2 source (referred to as the PuF_4 source) used at SRP seems to be unique. However, almost all the neutrons emanating from the source originate from $F(\alpha,n)$ sources. Figure 3.13 shows the spectrum from a PuF_4 calibration source used at Hanford, which shows a very similar spectral shape (Brackenbush and Faust 1970). The spectrum shown in Figure 3.13 was measured with ^{6}Li and ^{3}He sandwich spectrometers, which operate on a completely different principal than the neutron spectrometer used at SRP. The plots of neutron flux versus energy from the NE-213 spectrometer in Figure 3.10 agrees closely with the spectrum shown in Figure 3.13.

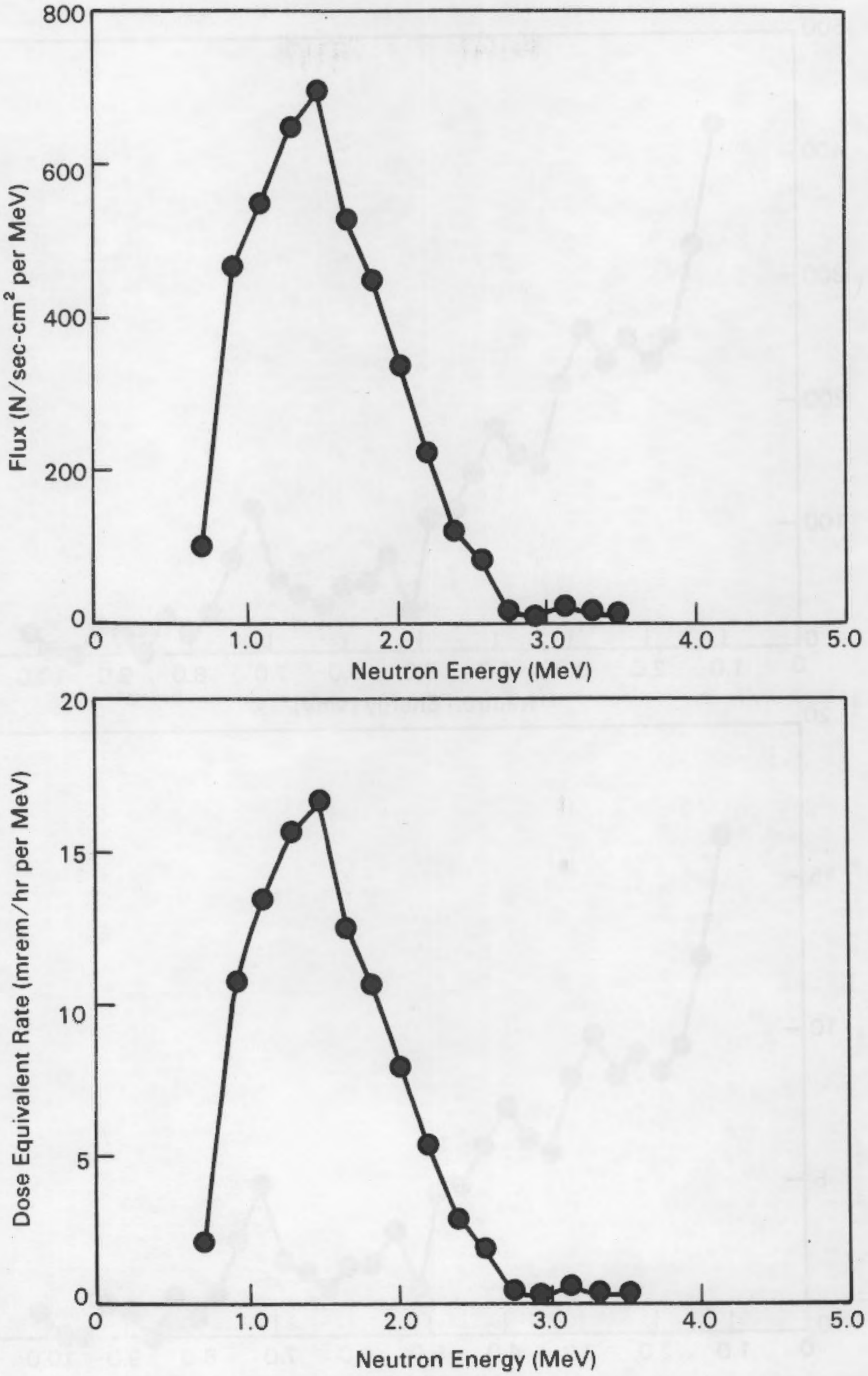


FIGURE 3.10. Neutron Flux and Dose Equivalent Distributions Measured by the NE-213 Spectrometer at 81 cm from the PuF_4 Calibration Source

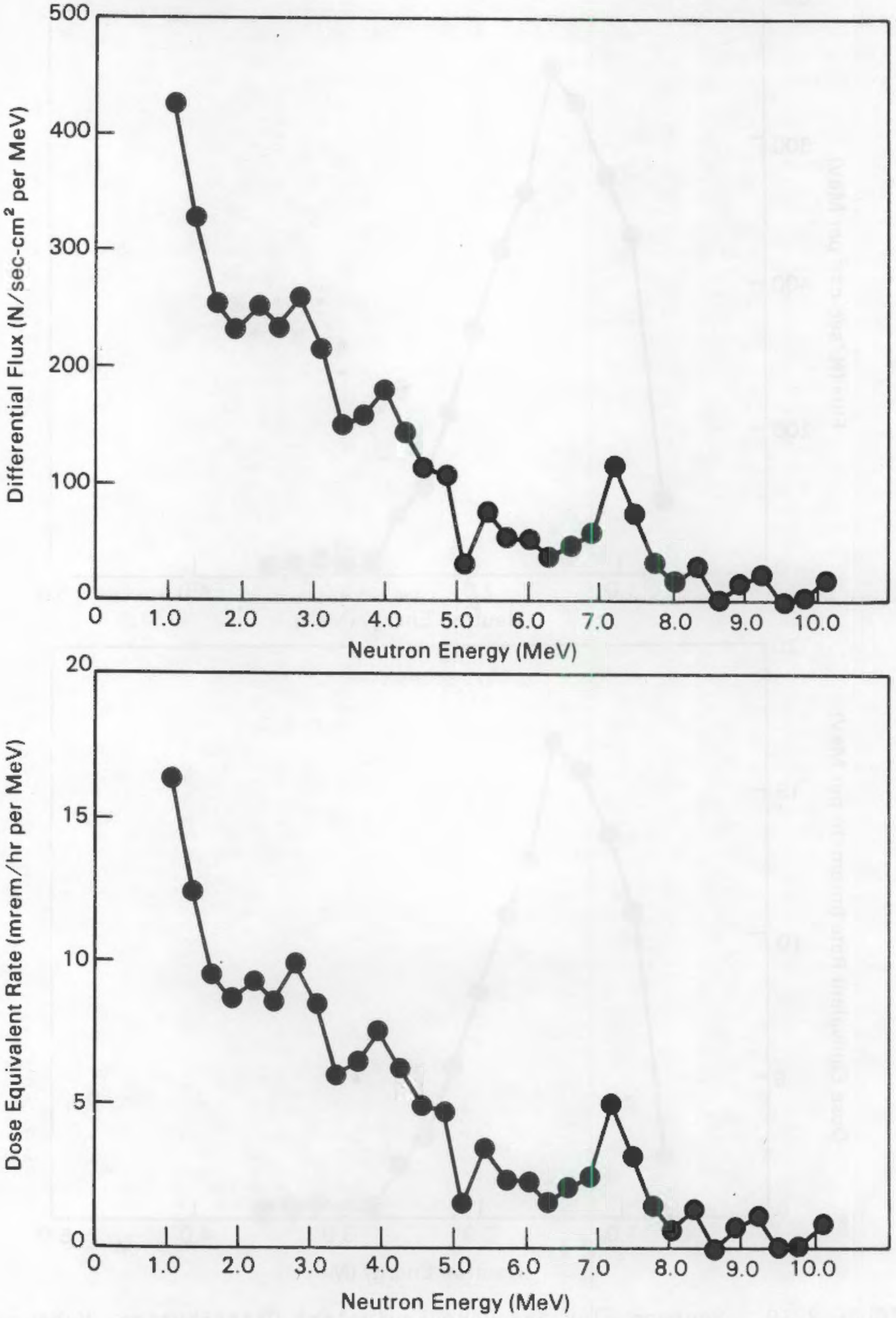


FIGURE 3.11. Neutron Flux and Dose Equivalent Distributions Measured by the NE-213 Spectrometer at 81 cm from the PuBe Source at the Surface of the D_2O Tank

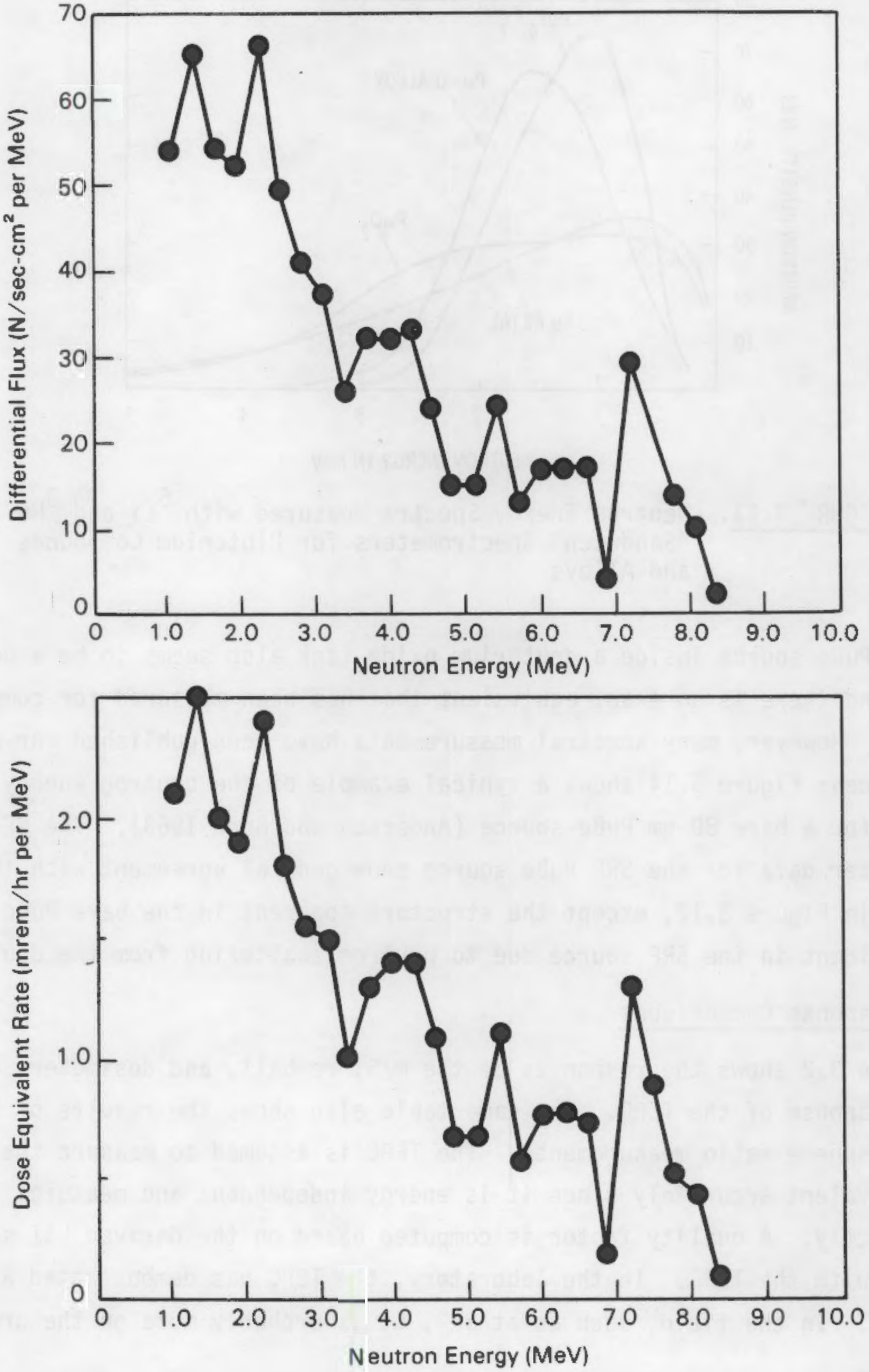


FIGURE 3.12. Neutron Flux and Dose Equivalent Distributions Measured by the NE-213 Spectrometer at 81 cm from the PuBe Source at a Depth of 150 mm in the D_2O Tank

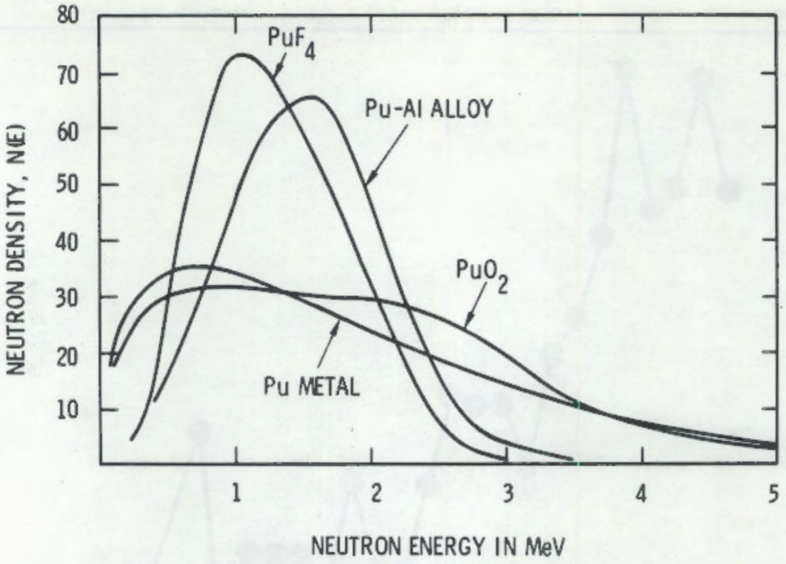


FIGURE 3.13. Neutron Energy Spectra Measured with ^{6}Li and ^{3}He "Sandwich" Spectrometers for Plutonium Compounds and Alloys

The PuBe source inside a deuterium oxide tank also seems to be a unique source, and there is no exact equivalent that has been measured for comparison purposes. However, many spectral measurements have been published for bare PuBe sources; Figure 3.14 shows a typical example of the neutron energy spectrum for a bare 80 gm PuBe source (Anderson and Bond 1963). The NE-213 spectrometer data for the SRP PuBe source show general agreement with the spectrum in Figure 3.12, except the structure apparent in the bare PuBe source is not evident in the SRP source due to neutron scattering from the deuterium.

3.1.5 Response Comparisons

Table 3.2 shows the responses of the M/S, remball, and dosimeters divided by the response of the TEPC. The same table also shows the results of the 9- to 3-in. sphere ratio measurements. The TEPC is assumed to measure the neutron dose equivalent accurately since it is energy independent and measures absorbed dose directly. A quality factor is computed based on the derived LET spectrum obtained with the TEPC. In the laboratory, the TEPC has demonstrated an accuracy within 5%. In the field, such as at SRP, it is probably more on the order of 10 to 20%.

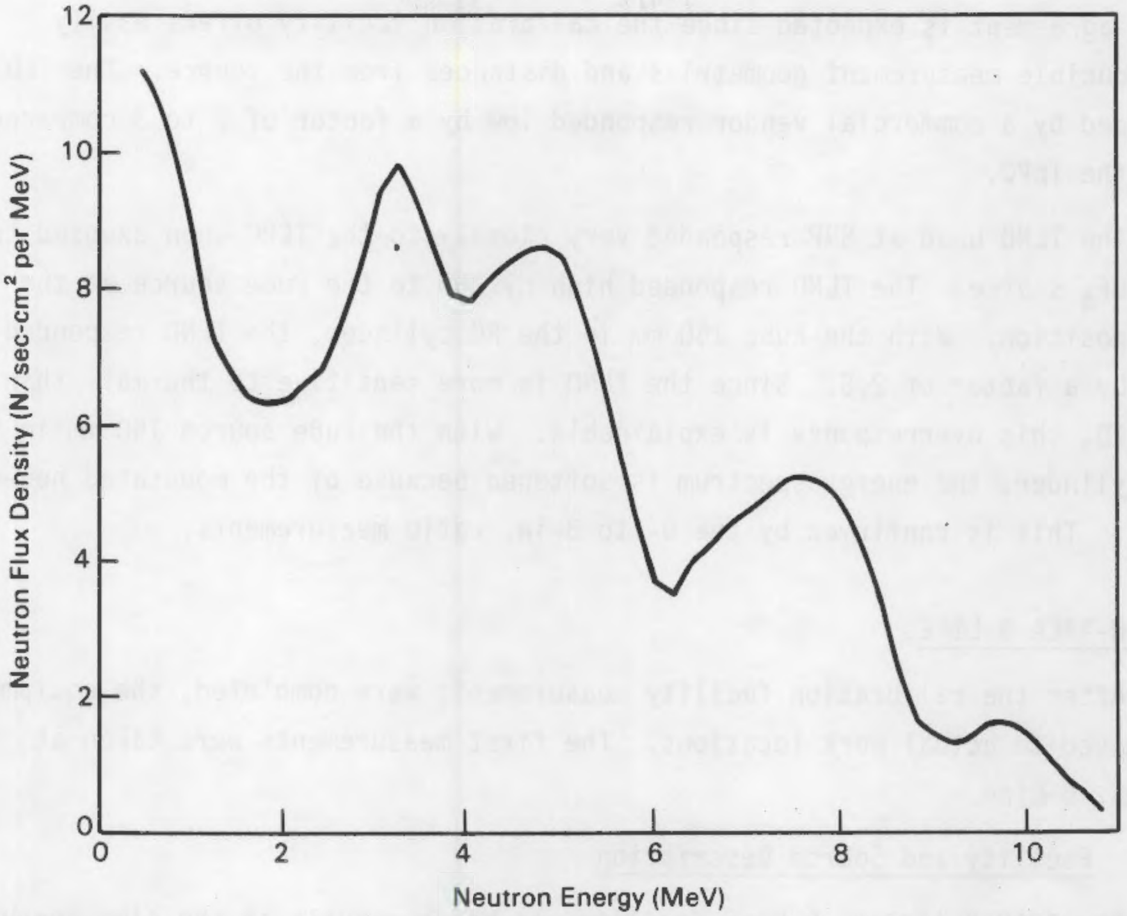


FIGURE 3.14. Neutron Energy Flux for an Unmoderated PuBe Neutron Source

TABLE 3.2. Response of Instruments and Dosimeters Divided by the TEPC Response at the Calibration Facility

Source	M/S	^{3}He	Remball (PNR-4)	PNL TED	LLNL TED	Commercial TED	TLND	9 in./3 in.
PuF_4 with drum	0.9	-	1.1	0.9	1.1	0.3	1.0	0.95
PuF_4 without drum	0.9	1.1	1.1	1.2	1.2	0.3	1.0	0.95
PuBe, 0 mm	0.8	1.0	1.1	1.0	0.9	0.7	1.2	0.43
PuBe, 150 mm	1.0	1.1	1.3	0.9	0.8	0.6	2.5	0.19

The multisphere system and the ^{3}He spectrometer showed excellent agreement with the TEPC, computing neutron dose equivalent rates generally within 10% of the values measured by the TEPC. The TEDs supplied by PNL and LLNL also agreed closely with the TEPC for both the PuBe and PuF_4 sources. This close agreement is expected since the calibration facility offers easily reproducible measurement geometries and distances from the source. The TED provided by a commercial vendor responded low by a factor of 2 to 3 compared with the TEPC.

The TLND used at SRP responded very closely to the TEPC when exposed to the PuF_4 source. The TLND responded high by 20% to the PuBe source at the 0-mm position. With the PuBe 150 mm in the RO cylinder, the TLND responded high by a factor of 2.5. Since the TLND is more sensitive to thermals than the TED, this overresponse is explainable. With the PuBe source 150 mm in the D_2O cylinder, the energy spectrum is softened because of the moderated neutrons. This is confirmed by the 9- to 3-in. ratio measurements.

3.2 H-AREA B-LINE

After the calibration facility measurements were completed, the equipment was moved to actual work locations. The first measurements were taken at H-Area, B-Line.

3.2.1 Facility and Source Description

The 221H Building, B-Line facility was being rebuilt at the time measurements were taken so it contained no radioactive contamination. Four $^{238}PuO_2$ sources, listed in Table 3.3, were placed in EP-61 containers. The four EP-61 containers were placed in a vertical array in an open-faced hood in Room 512 for the first set of measurements, as shown in Figure 3.15.

The four sources in the EP-61 containers were then moved to Glovebox #4 in Room 519 for another set of measurements. The front of the glovebox contains a 16.5-cm (6.5-in.) thick glass shield (1.50 in. of lead glass, 0.25-in. acrylic plastic, 4.25-in. laminated glass, and 0.50-in. plate glass). The four sources were arranged as shown in Figure 3.16, so that the center two sources were shielded by the glass and the outside two sources were approximately in the center of open glove ports. The source array was positioned approximately 30 cm (12 in.) from the glovebox wall, as measured on the floor of the glovebox.

TABLE 3.3. ^{238}Pu Sources Contained in EP-61 Containers

Source	(875) 1	(894) 2	(898) 3	(960) 4
	du Pont Source Identification Number			
Mass of ^{238}Pu	129.4 g	181.0 g	158.5 g	157.5 g

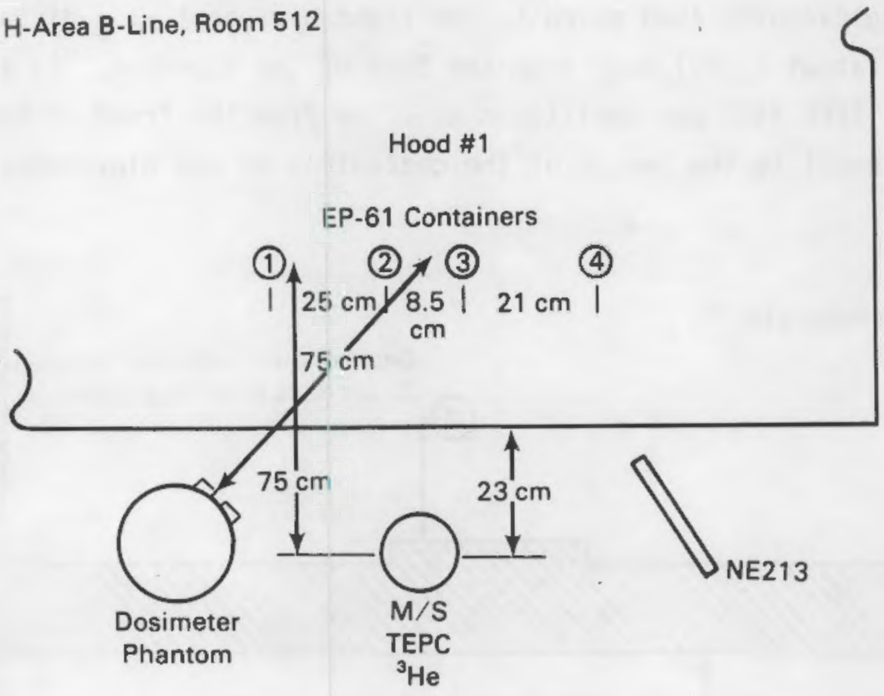


FIGURE 3.15. Measurement Locations Near Hood #1 in B-Line of H-Area

3.2.2 Measurement Locations

Measurements were first conducted with the sources in the open-faced hood in Room 517. Figure 3.15 shows the positions of the instruments relative to the sources. All of the detectors were positioned at a height of 109 cm (43 in.) above the floor, which is a typical elevation of a TLND dosimeter worn on the belt. TEPC #501 was positioned on the center line of the source array at a distance of 75 cm from the center of the sources. The NE-213 detector was positioned next to TEPC #501, and a water phantom containing dosimeters was positioned to the left side at a distance of about 75 cm from the source array. A ^{3}He spectrometer was placed behind the $^{238}PuO_2$ source array at an estimated distance of 75 cm from the array. The exact distance is not known because of an air duct was located at the back of the hood.

After the sources were moved to Glovebox #4, measurements were made in Room 514 behind the glovebox. Figure 3.16 shows the measurement location. All detectors and the dosimeters were 109 cm above the floor.

Measurements were first made with the multisphere spectrometer placed between the gloveports then moved to the right gloveport at a distance of about 17 cm (about 7 in.) away from the face of the glovebox. As shown in Figure 3.17, TEPC #501 was positioned at 17 cm from the front of the glovebox at a height equal to the height of the centerline of the gloveports, about

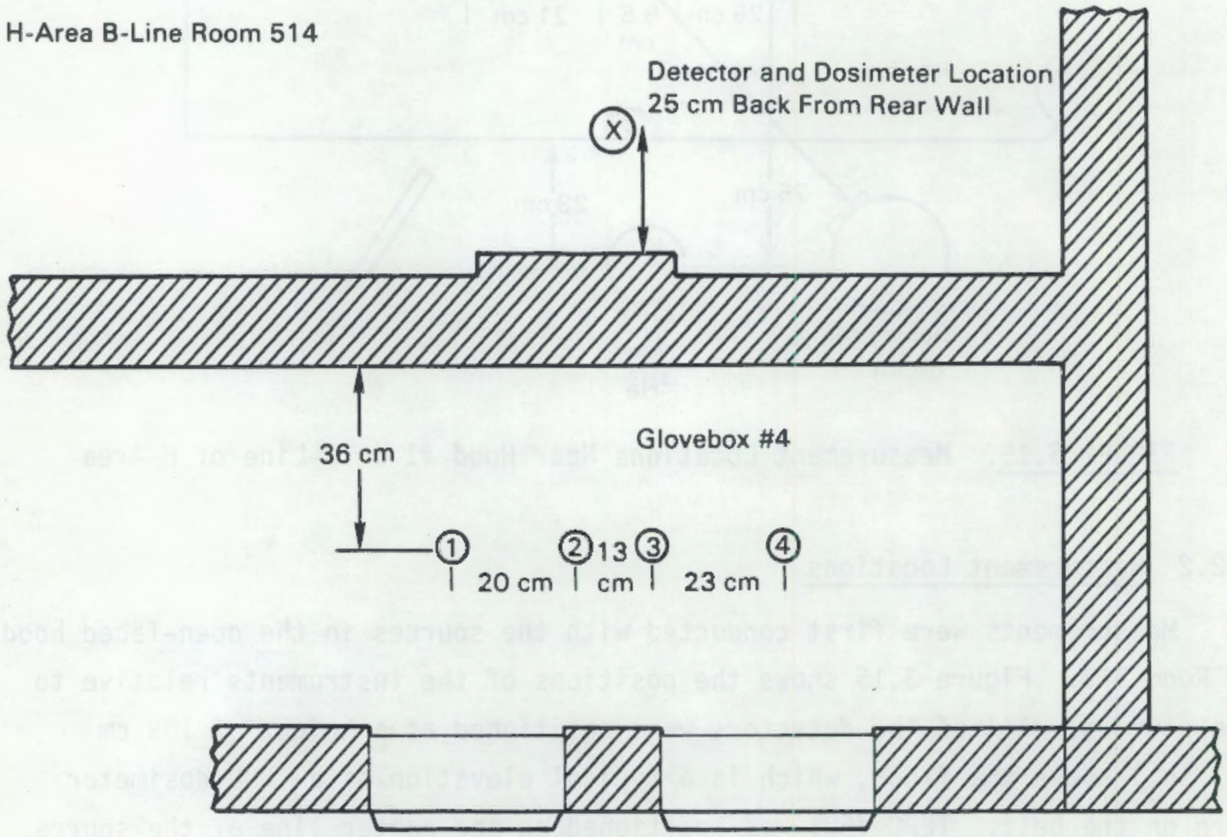


FIGURE 3.16. Source Locations in Glovebox #4 in B-Line of H-Area

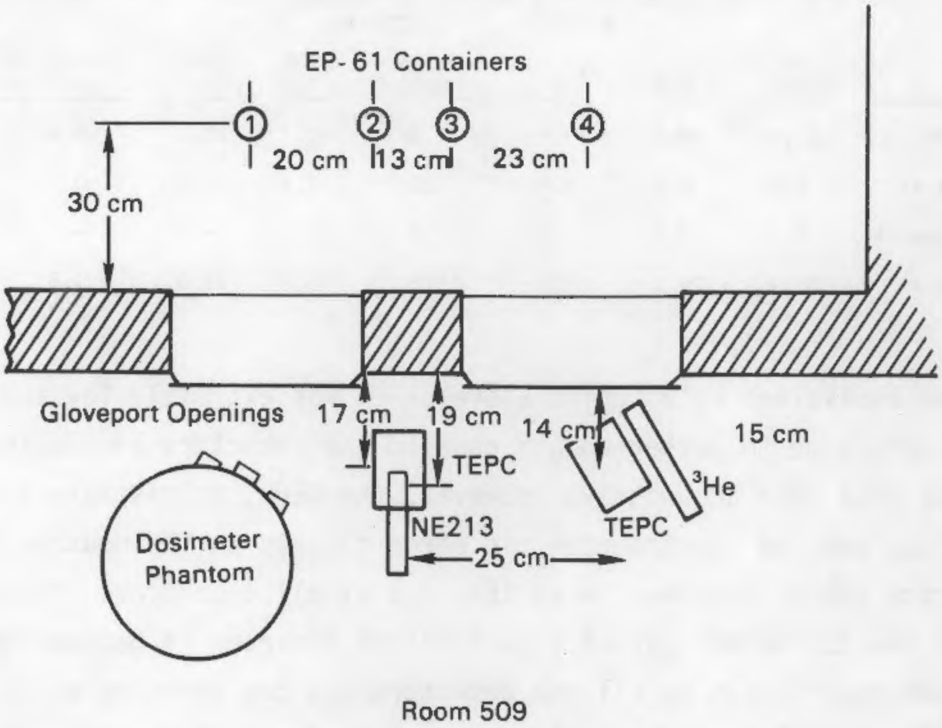


FIGURE 3.17. Measurement Locations in Front of Glovebox #4 in B-Line of H-Area

131 cm or 51.5 in. above the floor. The NE-213 spectrometer was placed immediately above TEPC #501 and about 19 cm back from the glovebox wall. TEPC #184 was positioned at the center of the right gloveport about 14 cm from the glovebox wall, and the ^{3}He spectrometer was positioned adjacent to TEPC #184. Dosimeters on a water phantom were positioned at a distance of 15 cm (6 in.) from the left gloveport. Ideally, measurements should have been made with the dosimeters placed at the same locations as the TEPCs and multisphere measurements on the centerline between the gloveports and at the center of the gloveport, but this was not possible because of time limitations.

3.2.3 Neutron Dose Equivalent Rates

Table 3.4 gives the neutron dose equivalent rates in the B-Line of H Area.

TABLE 3.4. Neutron Dose Equivalent Rates (mrem/h) in the B-Line of H Area

Source	TEPC	M/S	^{3}He	Remball (PNR-4)	PNL TLD	LLNL TLD	Commercial TED	TLND
Front of Hood #1	21.1	19.4	19.4	27.0	18.7	20.2	6.2	8.6
Behind Glovebox #4	0.9	0.8	1.4	1.0	2.4	1.2	0	1.0
Front of Glovebox #4	5.2	6.0	7.2	7.5	-	-	-	-
Through Gloveport of Glovebox #4	15.1	14.2	13.0	19.5	15.7	28.0	3.8	11.6

The dose equivalent rate behind Glovebox #4 was extremely low and there was insufficient time to gather enough dose on the detectors and dosimeters to determine the dose rate accurately. However, the TEPC, multisphere spectrometer (M/S), and ^{3}He spectrometer did agree closely on the neutron dose equivalent rate behind Glovebox #4 as they did at all locations. There are no readings for the dosimeters directly in front of Glovebox #4 because there was not sufficient room to put up all the detectors and two phantoms simultaneously. Therefore, only one phantom was set up in front of the gloveport at Glovebox #4.

3.2.4 Neutron Energy Spectra

Figures 3.18 and 3.19 show the neutron flux per energy bin versus energy and the neutron dose equivalent rate per energy bin versus energy for the measurements made with the multisphere spectrometer along the B-line in H Area. Figure 3.20 shows the neutron dose equivalent rate versus energy measured by the ^{3}He spectrometer at the measurement locations in H Area. In Hood #1, since there was no shielding between the source and the detector, a hard neutron energy spectrum was measured. Figures 3.18 and 3.20 clearly shows that most of the dose is attributed to neutrons between 500 keV and 5 MeV. Even behind the Glovebox #4, where there was much shielding between the source and detector, most of the dose was caused from fast neutrons above 500 keV. In front of the glovebox, the M/S and ^{3}He were used to determine if there was a significant shift in neutron energy spectra through the gloveport as compared with through glovebox wall. There was a 10 to 20% increase in average neutron energy through the gloveport as compared with through the glovebox wall. Figures 3.19 and 3.20 show most of the dose in the 100 keV to few MeV energy range.

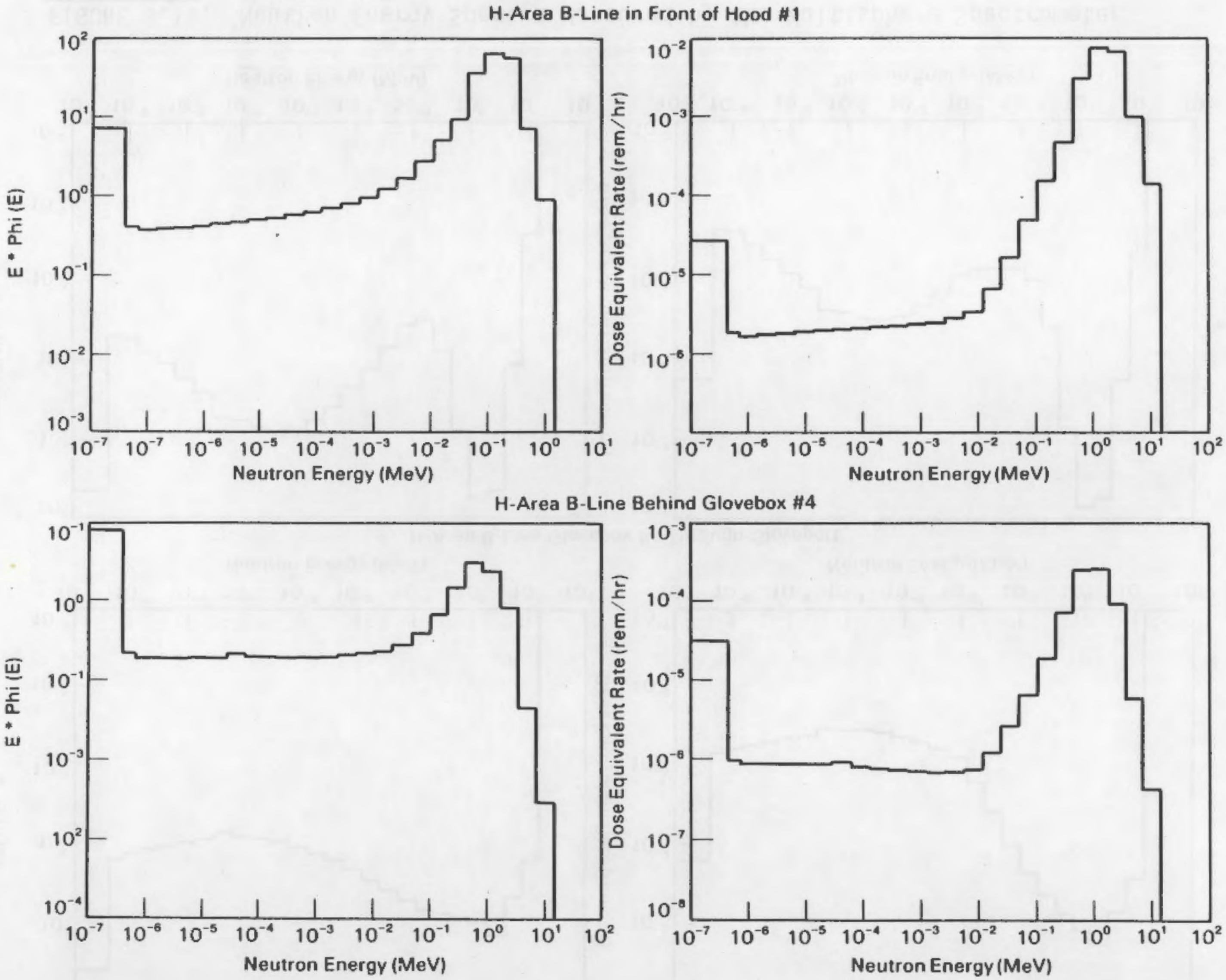
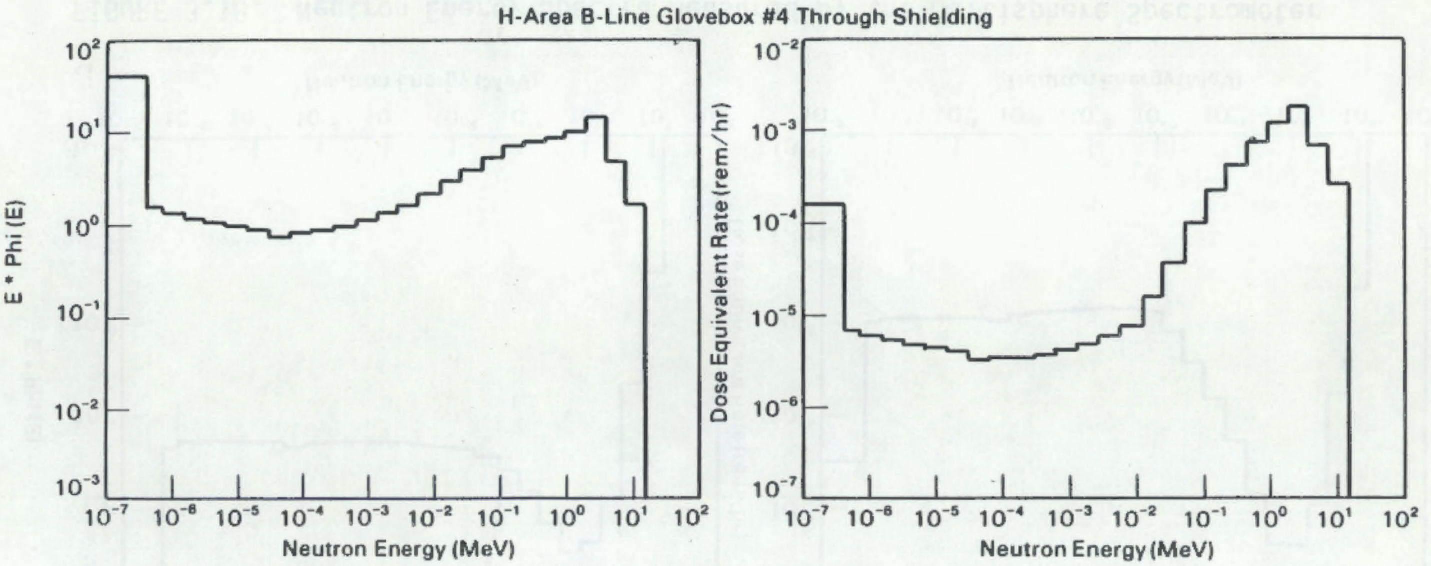


FIGURE 3.18. Neutron Energy Spectra Measured by the Multisphere Spectrometer in Rooms 512 and 514


H-Area B-Line Glovebox #4 Through Shielding

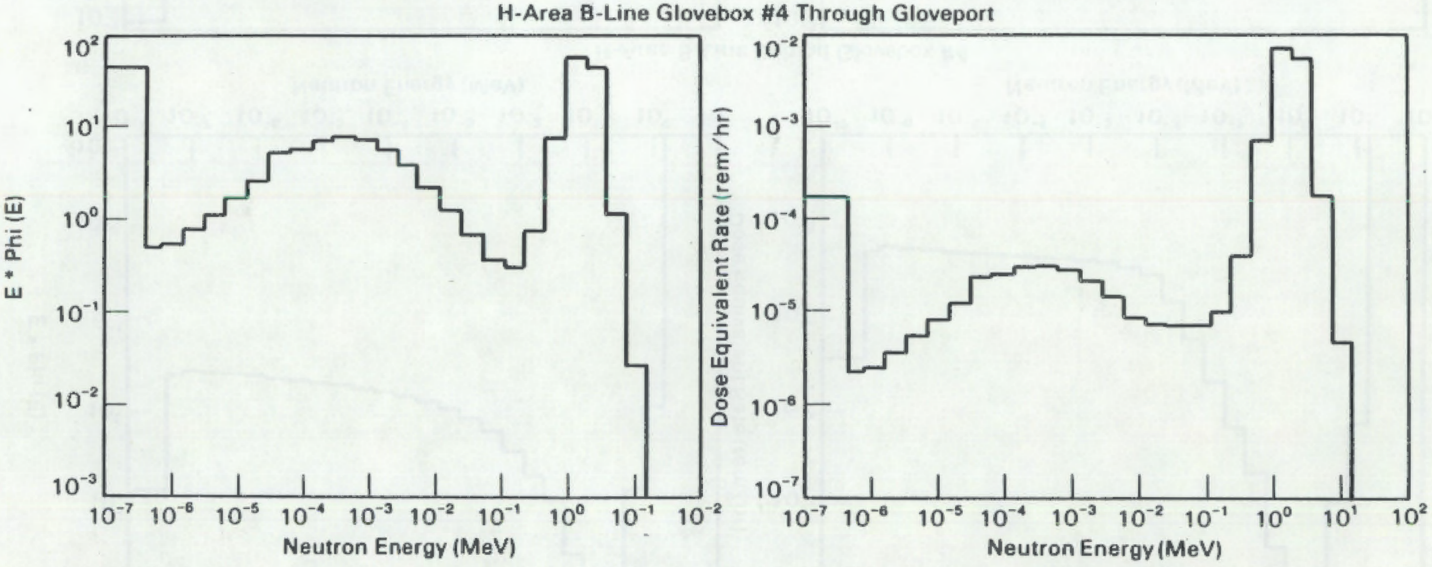

H-Area B-Line Glovebox #4 Through Gloveport

FIGURE 3.19. Neutron Energy Spectra Measured by the Multisphere Spectrometer in Room 509

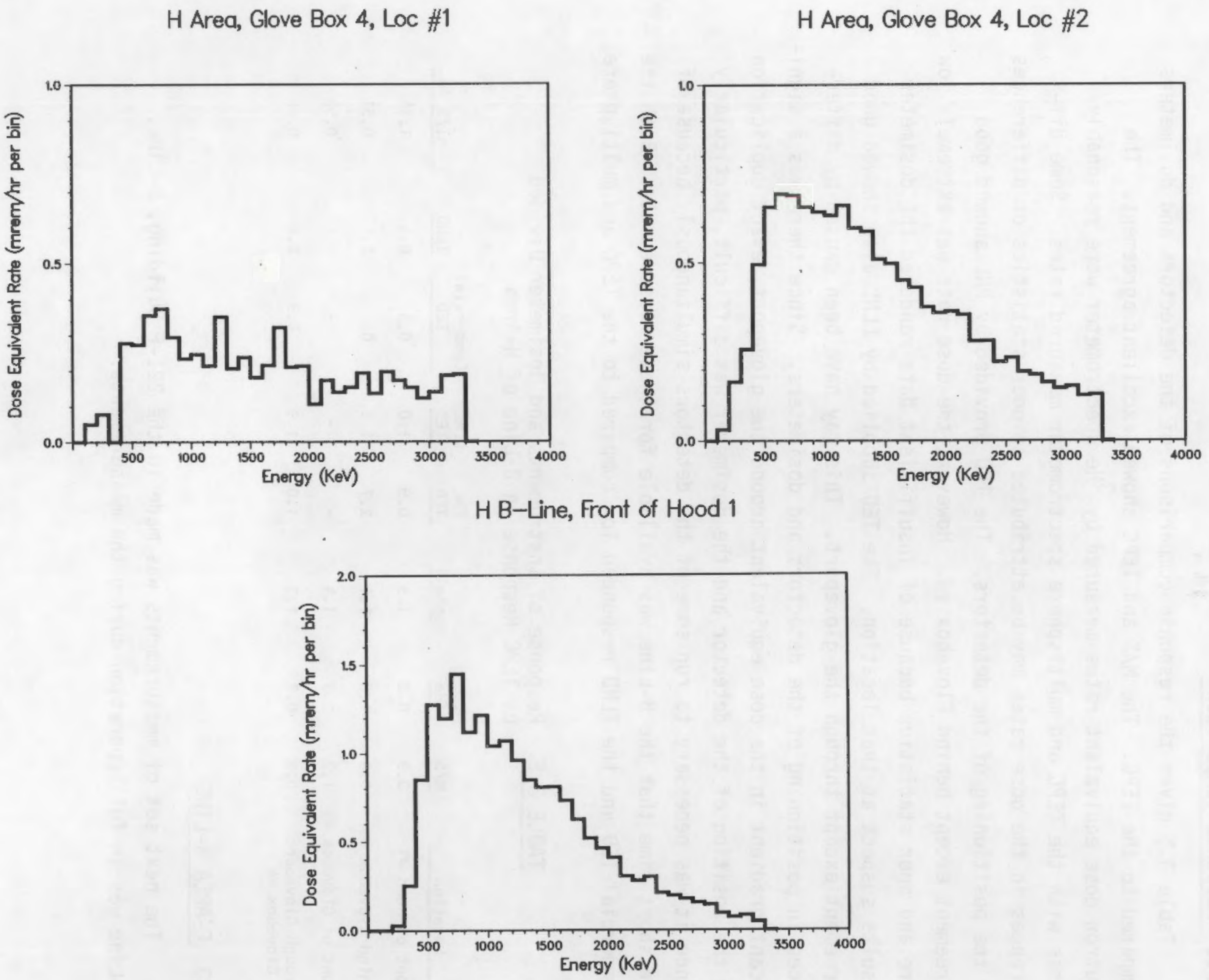


FIGURE 3.20. Neutron Dose Equivalent Rates in H-Area B-Line Determined from Neutron Energy Spectra Measured by the ^{3}He Spectrometer

3.2.5 Response Comparisons

Table 3.5 gives the response comparisons of the detectors and dosimeters compared to the TEPC. The M/S and TEPC showed excellent agreement. The neutron dose equivalent rates measured by ^{3}He spectrometer were reasonably close with the TEPC and multisphere spectrometer measured rates. Some differences in the dose rates may be.attributed to poor statistics or differences in the positioning of the detectors. The TED provided by PNL showed good agreement except behind Glovebox #4. However, the dose rate was extremely low here and poor statistics because of insufficient data rendered the dosimeter results suspect at that location. The TED supplied by LLNL also showed good agreement except through the gloveport. This may have been caused by differences in positioning of the detectors and dosimeters. Since there was a significant gradient in the dose equivalent around the gloveport, exact duplication in the position of the detector and the dosimeter was difficult, particularly since it was necessary to run some of the detectors simultaneously because of the short time that the B-Line was available for these measurements. Both the commercial TED and the TLND responded low compared to the TEPC and multisphere.

TABLE 3.5. Response of Instruments and Dosimeter Divided by TEPC Response in B-Line of H-Area

Location	M/S	^{3}He	Remball	PNL TED	LLNL TED	Commercial TED	TLND	9 in./3 in.
Front of Hood #1	0.9	0.8	1.3	0.9	1.0	0.3	0.4	1.44
Behind Glovebox #4	0.9	1.6	1.1	2.7	1.3	0	1.1	0.51
Front of Glovebox #4	1.2	1.3	1.4	-	-	-	-	0.53
Through Gloveport of Glovebox #4	0.9	0.8	1.3	1.0	1.9	0.3	0.8	0.88

3.3 F-AREA B-LINE

The next set of measurements was made in the 221-F Building, B-Line. B-Line was in full operation during the measurements.

3.3.1 Facility and Source Description

The B-Line area was in full production while some construction work was being scheduled. There was a potential for contaminating the equipment and for interference with production schedules, so only a limited number of measurements were possible.

3.3.2 Measurement Locations

Measurements were made on the wing cabinet in Mechanical Line Operating Room 2 (MLOR2), which contained two boats filled with $^{238}PuF_4$. The first measurement position was 20 cm (8 in.) away from the gloveport on the left side, centered upon the gloveport; the second measurement position was 20 cm (8 in.) away from the glovebox on the right side, centered between the glove ports. As before, measurements were made with the multisphere spectrometer positioned at 109 cm (43 in.) above the floor, which is the approximate position of a TLND worn on the belt of a worker.

After the multisphere spectrometer measurements were completed additional measurements were made at the same locations with the TEPCs and the spectrometers. As shown in Figure 3.21, TEPC #502 was positioned at Location #1 on the left side of the wing cabinet with the NE-213 spectrometer placed next to it in front of the gloveport. TEPC #184 was located at Position 2 at 20 cm (8 in.) away centered between the gloveports. The ^3He spectrometer was positioned just behind TEPC #184 at 33 cm (13 in.) away and 130 cm (51 in.) above the floor. A second set of measurements was made with the TEPCs in the same positions and the NE-213 spectrometer with ^3He spectrometers positions reversed. At a later time, water phantoms with TLND and CR-39 neutron dosimeters were placed at Positions 1 and 2.

Measurements were then made in the center of the precipitator operating room (POR) at a height of 109 cm (43 in.) above the floor. Figure 3.22 shows the detector locations. This room contained gloveboxes full of material being processed, and workers entered the room occasionally to operate equipment. It is possible that the dose rates may have changed during the measurements. The gloveboxes were heavily shielded with lucite, but there were numerous openings

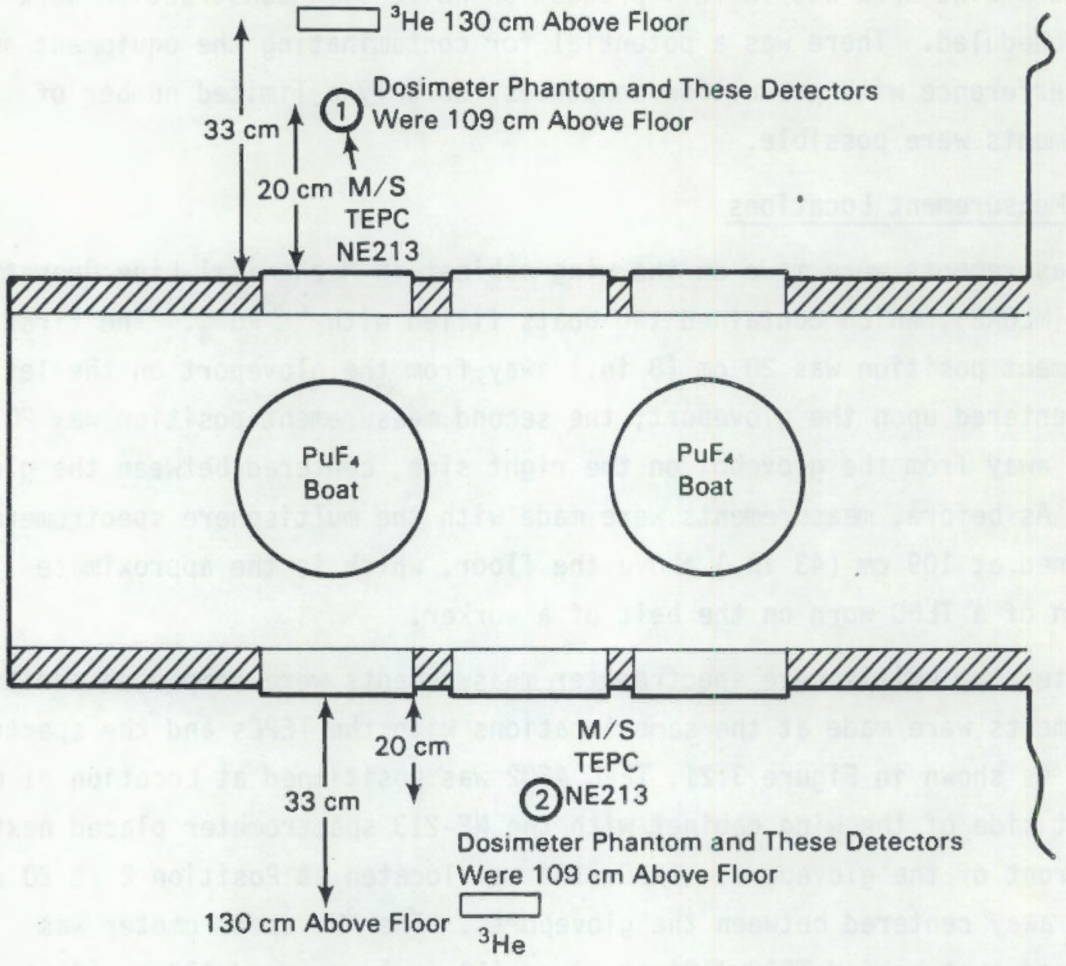


FIGURE 3.21. Measurement Locations Near Wing Cabinet in MLOR2 in B-Line of F-Area

where streaming occurred. Measurements made at the center of the room away from openings in the lucite shields should yield an average neutron energy spectrum.

Measurements were first made with the multisphere spectrometer, then it was removed and measurements were made overnight with the TEPC placed at the same location. The other spectrometers were then located nearby. At a later time a water phantom containing TLND and CR-39 dosimeters were placed at the center of the room.

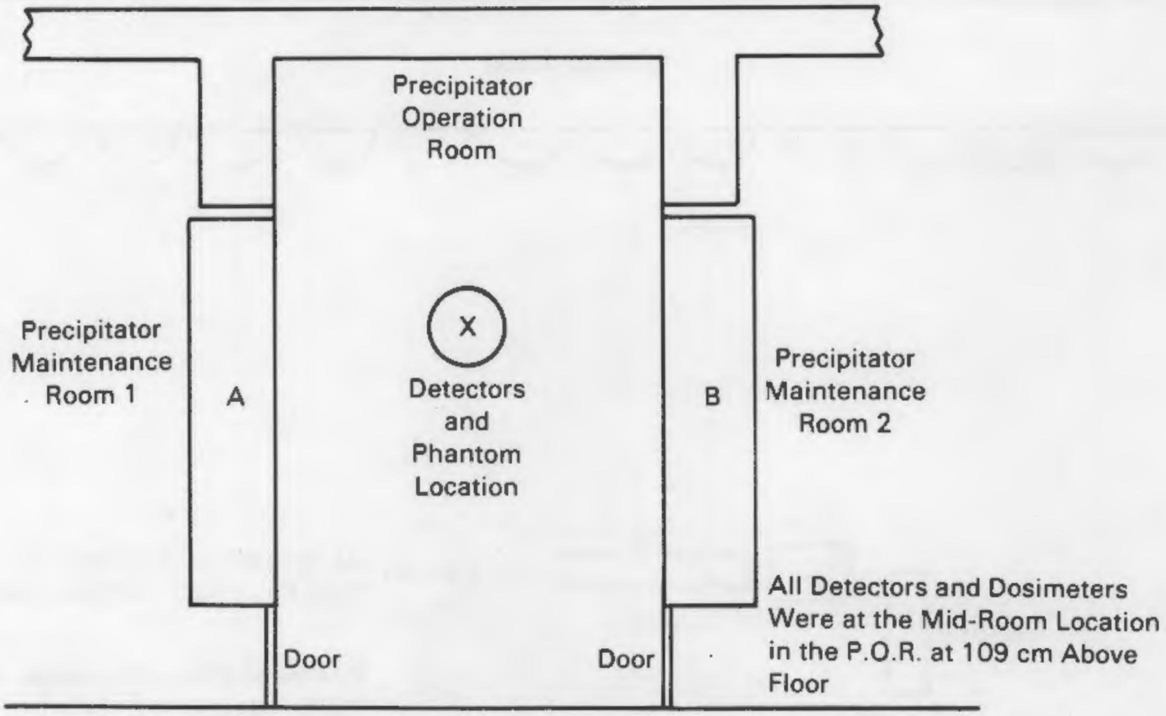


FIGURE 3.22. Measurement Locations in the POR in B-Line of F-Area

The equipment was then moved to a plutonium storage area and positioned at 91 cm (3 ft) away from a wall containing cans of plutonium in storage. Preliminary surveys with a survey instrument showed little variation in dose rates with position, so TEPC #501, the multisphere spectrometer, the NE-213 spectrometer and the ^{3}He spectrometer were positioned as shown in Figure 3.23 and left overnight to collect data. The SRP neutron survey instrument indicated a neutron dose equivalent rate of 30 mrem/h, and the SRP Eberline RO-2 survey instrument indicated a gamma exposure rate of 60 mR/h at 91 cm (3 ft) from the wall.

3.3.3 Neutron Dose Equivalent Rates

Neutron measurements were performed at four locations in F Area: three locations along B-Line and one in the plutonium storage area. Table 3.6 gives the neutron dose equivalent rates. Two measurements were made near Glovebox MLOR2. One measurement was made through the gloveport to examine the effects of streaming on the neutron dose equivalent and on the energy spectrum. In

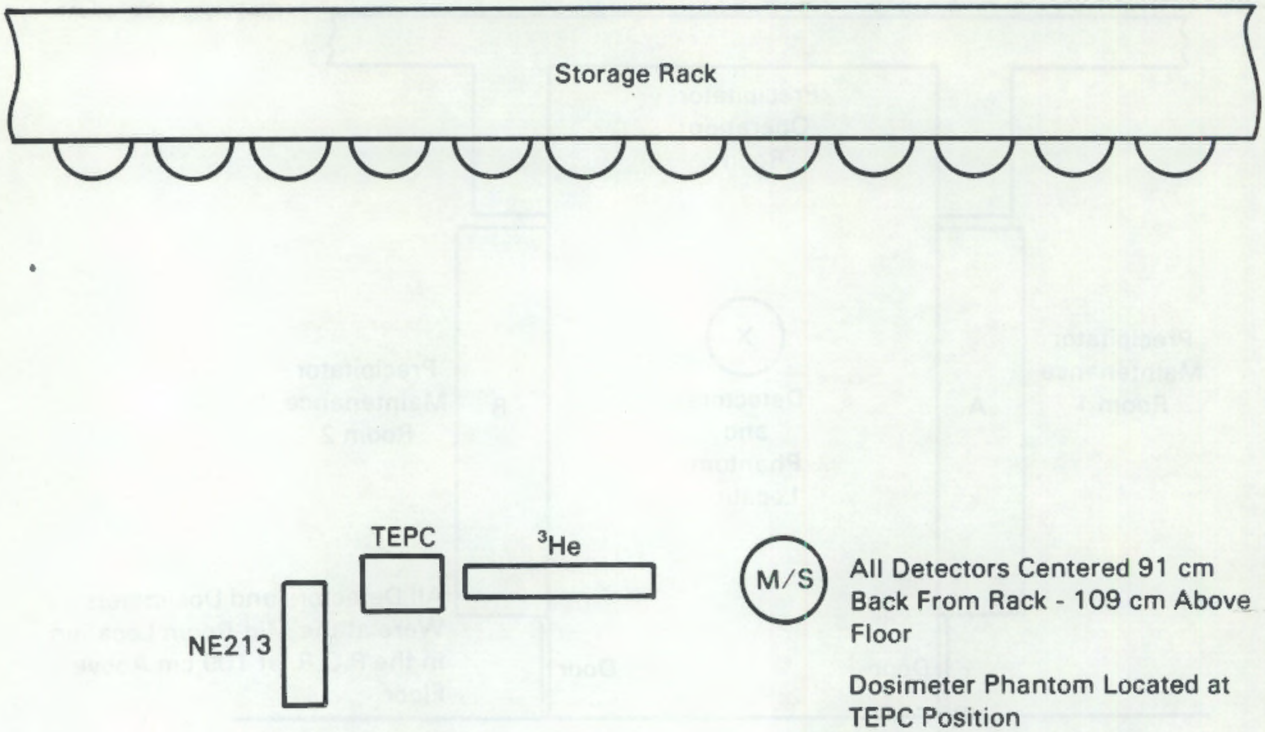


FIGURE 3.23. Measurement Locations in the Plutonium Storage Area in F-Area

TABLE 3.6. Neutron Dose Equivalent Rates (mrem/h) in F-Area

Location	TEPC	M/S	^{3}He	Remball (PNR-4)	PNL TED	LLNL TED	Commercial TED	TLND
MLOR2 Glovebox, through gloveport	33.4	31.8	19.7	40	12.0	20.5	4.31	40.3
MLOR2 Glovebox, through center of glovebox	47.8	37.0	27.3	47	15.0	26.5	6.7	42.3
POR	4.0	3.1	3.6	4.4	0.5	0.7	0	2.6
Plutonium Storage Area	15.7	14.5	16.5	21	4.6	6.9	2.0	20.6

H-Area, the dose rate went up a factor of 3 through the gloveport compared with the center of the glovebox. However, the detectors were significantly further from the sources when positioned in front of the gloveports, than when positioned by the center of the box (see Figure 3.21). This accounts for the increased dose rate at the center of the box instead of through the gloveport as in the B-Line of H Area. The dose rate measured in the POR was relatively low as it was not in operation at the time of the measurements.

Measurements in the plutonium storage area were conducted along the west wall at a location yielding the highest neutron dose rates based on survey readings.

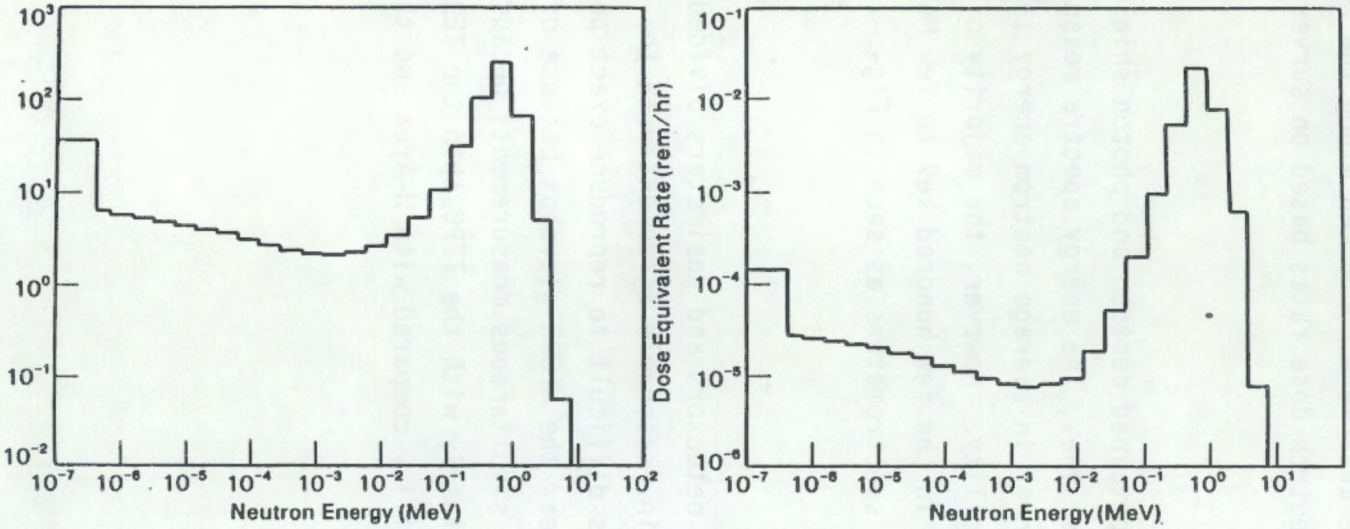
3.3.4 Neutron Energy Spectra

Gloveboxes in the B-Line of F-Area contained neutron and photon shielding and some residual plutonium in the process line. The energy spectra measured in F-Area B-Line were more degraded and lower in average neutron energy than measured at H Area and the calibration facility. However, the majority of neutron dose was attributed from neutrons in the few hundred keV to few MeV range measured by the multisphere and ^{3}He spectrometers as seen in Figures 3.24, 3.25, and 3.26.

3.3.5 Response Comparisons

Table 3.7 gives the responses of the detectors and dosimeters divided by the responses of the TEPC. The TEPC was in reasonable agreement with the multisphere and ^{3}He spectrometers. It was difficult to reproduce exact positioning of the detectors and dosimeters near the MLOR2 glovebox because of the cramped space and the need to conduct simultaneous measurements because of time constraints. The TLND agreed more closely with the TEPC than the TEDs because of the softer spectra in this facility compared with H-Area and the calibration sources.

F-Area B-Line M.L.O.R. #2 with PuF₄ Boats Through Glovebox Shielding



F-Area B-Line M.L.O.R. #2 with PuF₄ Boats Through Gloveports

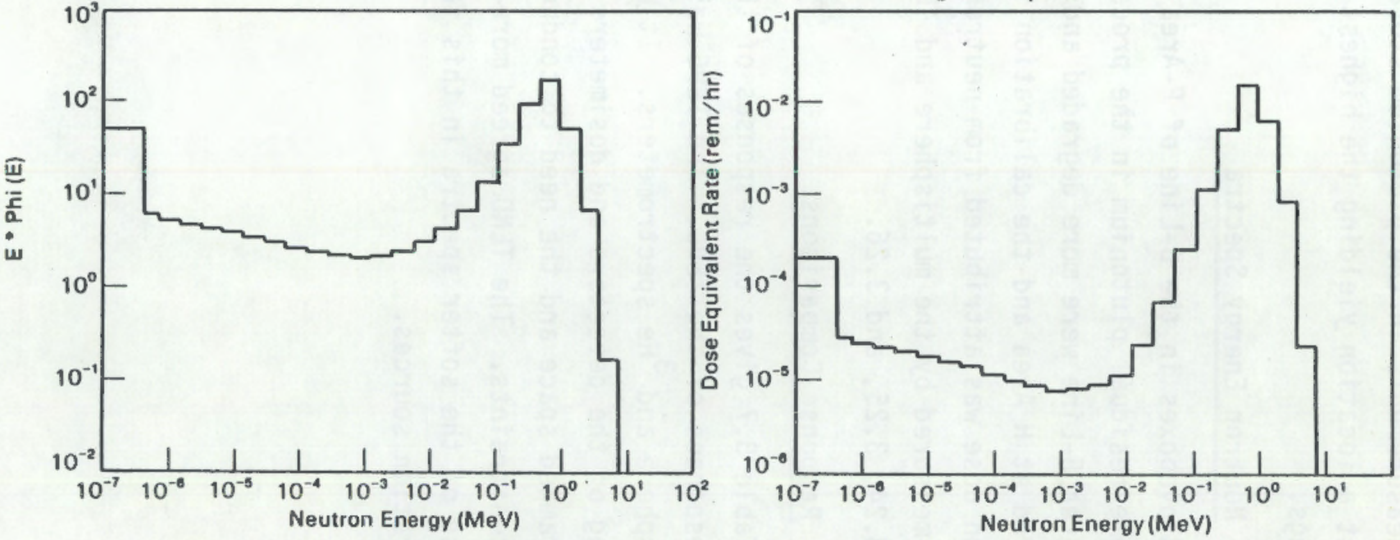


FIGURE 3.24. Neutron Energy Spectra Measured by the Multisphere Detector Near the MLOR2 Wing Cabinet in B-Line of F-Area

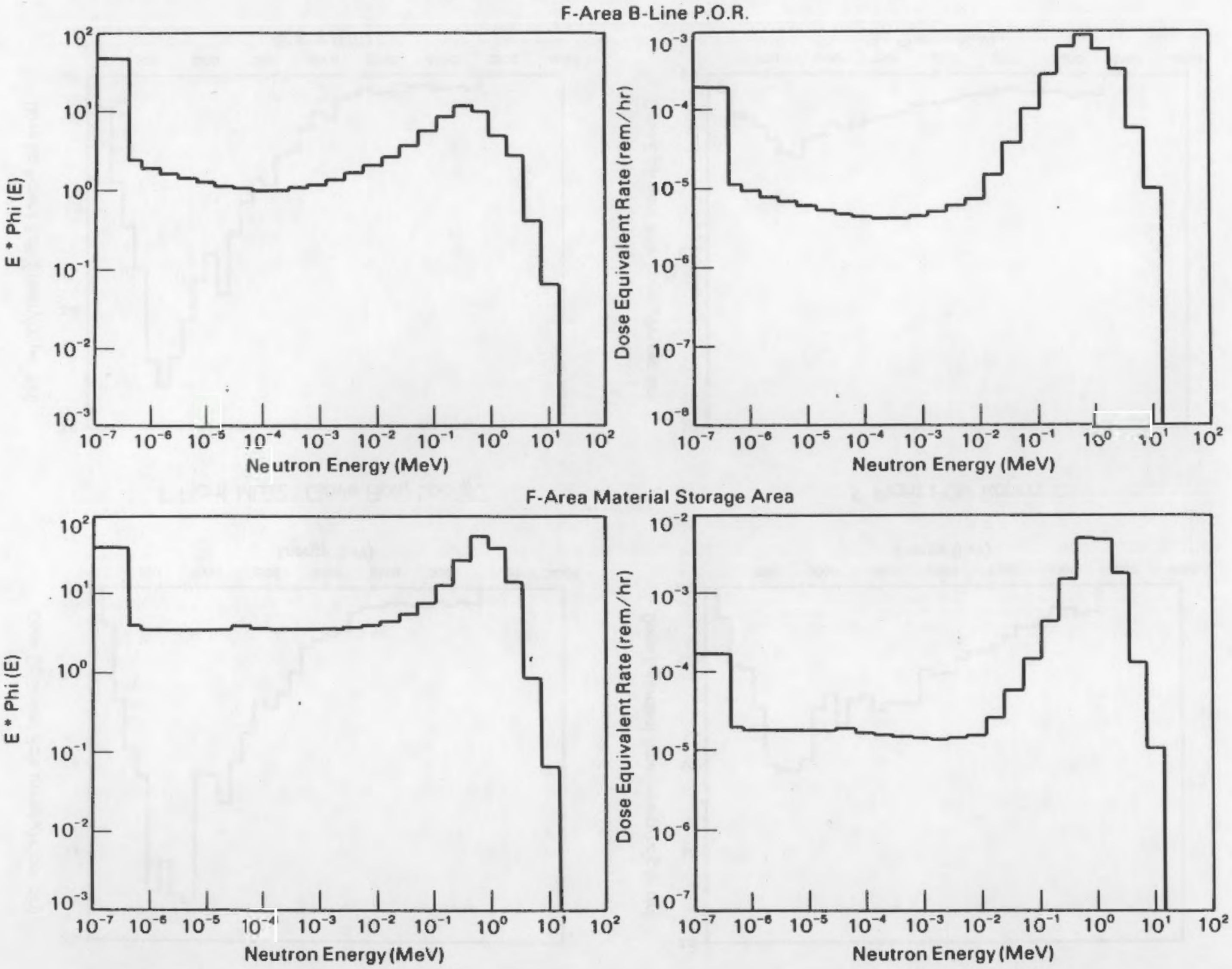


FIGURE 3.25. Neutron Energy Spectra Measured by the Multisphere Spectrometer in the POR and the Plutonium Storage Area in F-Area

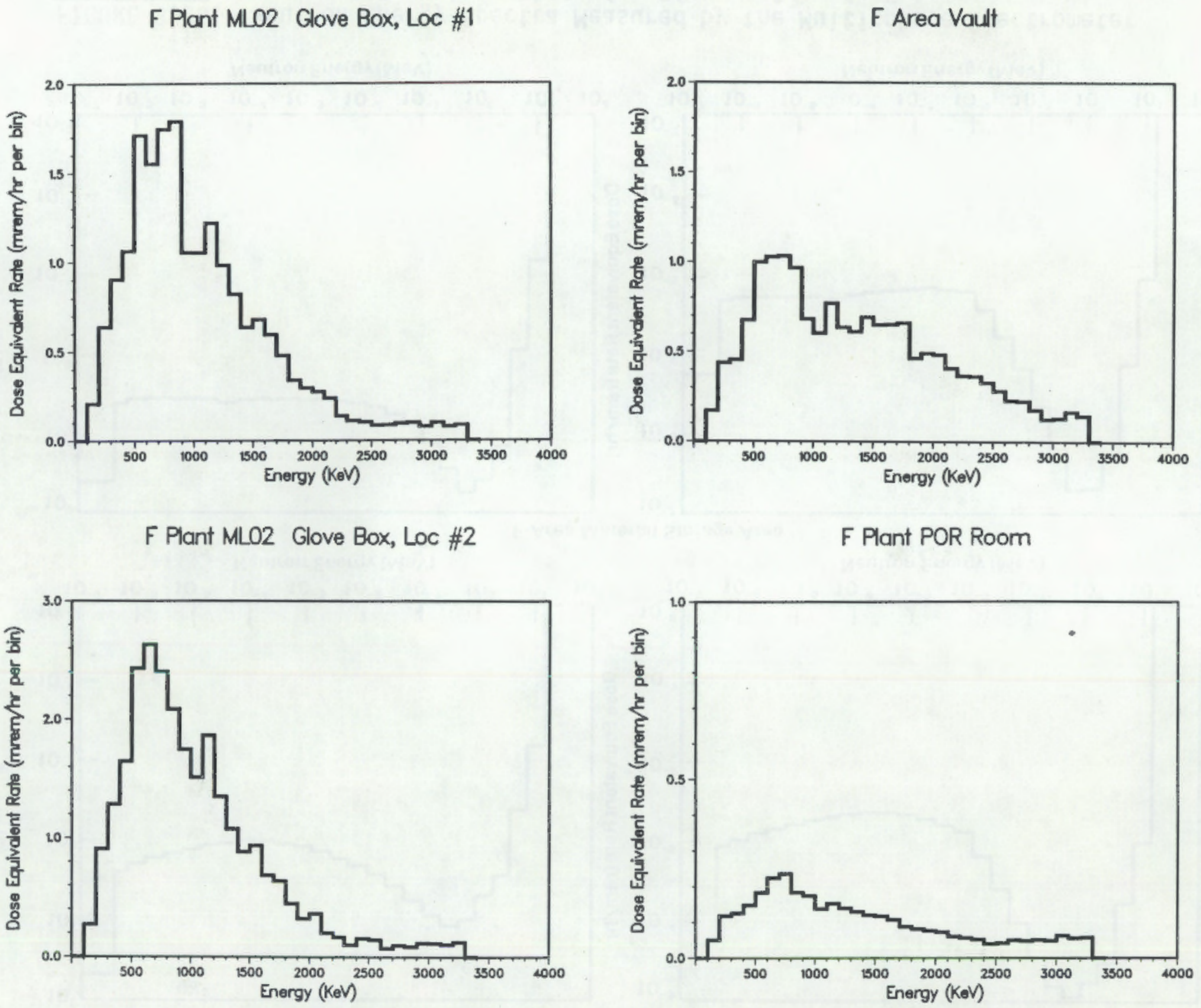


FIGURE 3.26. Neutron Dose Equivalent Rates in F-Area B-Line Determined from Neutron Energy Spectra Measured by the ^{3}He Spectrometer

TABLE 3.7. Response of the Detectors and Dosimeters Divided by the Response of the TEPC in B-Line of F-Area

Location	M/S	^{3}He	Remball (PNR-4)	PNL TED	LLNL TED	Commercial TED	TLND	9 in./3 in.
Glovebox MLOR2, through gloveport	1.0	0.6	1.2	0.4	0.6	0.1	1.2	0.52
Glovebox MLOR2, center of glovebox	0.8	0.6	1.0	0.3	0.6	0.1	0.9	0.61
POR	0.8	0.9	1.1	0.1	0.2	0	0.9	0.26
Pu Storage Area	0.9	1.1	1.3	0.3	0.4	0.1	1.3	0.41

3.4 ^{252}Cf FACILITY, 773-A BUILDING

Next, the equipment was moved to the ^{252}Cf facility. The gloveboxes were not used while the measurements were made, but contained residual Cf. The equipment was moved outside to the loading dock area and measurements were made on a shipping container loaded with Cf.

3.4.1 Facility and Source Description

Measurements were performed in the ^{252}Cf processing area located in the 773-A Building. The detectors were located near gloveboxes used to process ^{252}Cf waste material. No material was being processed at the time of the measurements. However, the gloveboxes did contain residual ^{252}Cf. The second source measured was a 16-mg ^{252}Cf source located in a 6-ft-diameter spherical polyethylene shipping cask containing neutron absorbers. The cask was labeled USA/6642/B, serial number L-23353 and weighed 4.5 tons.

3.4.2 Measurement Locations

As before, measurements were made at a height of 109 cm (43 in.) above the floor, which is representative of the height of a TLND dosimeter worn on a belt. Measurements were first made at two locations shown in Figure 3.27 near the ^{252}Cf remote loadout glovebox. Only nominal amounts of ^{252}Cf contamination were present, but the dose rates were quite high, even through the heavy shielding on the glovebox.

Position 1 was centered between the two gloveboxes at a distance of 46 cm (18 in.) out from the back. Position 2 was 20 cm (8 in.) out from the face of the glovebox and 91 cm (36 in.) out into the aisleway. This position was

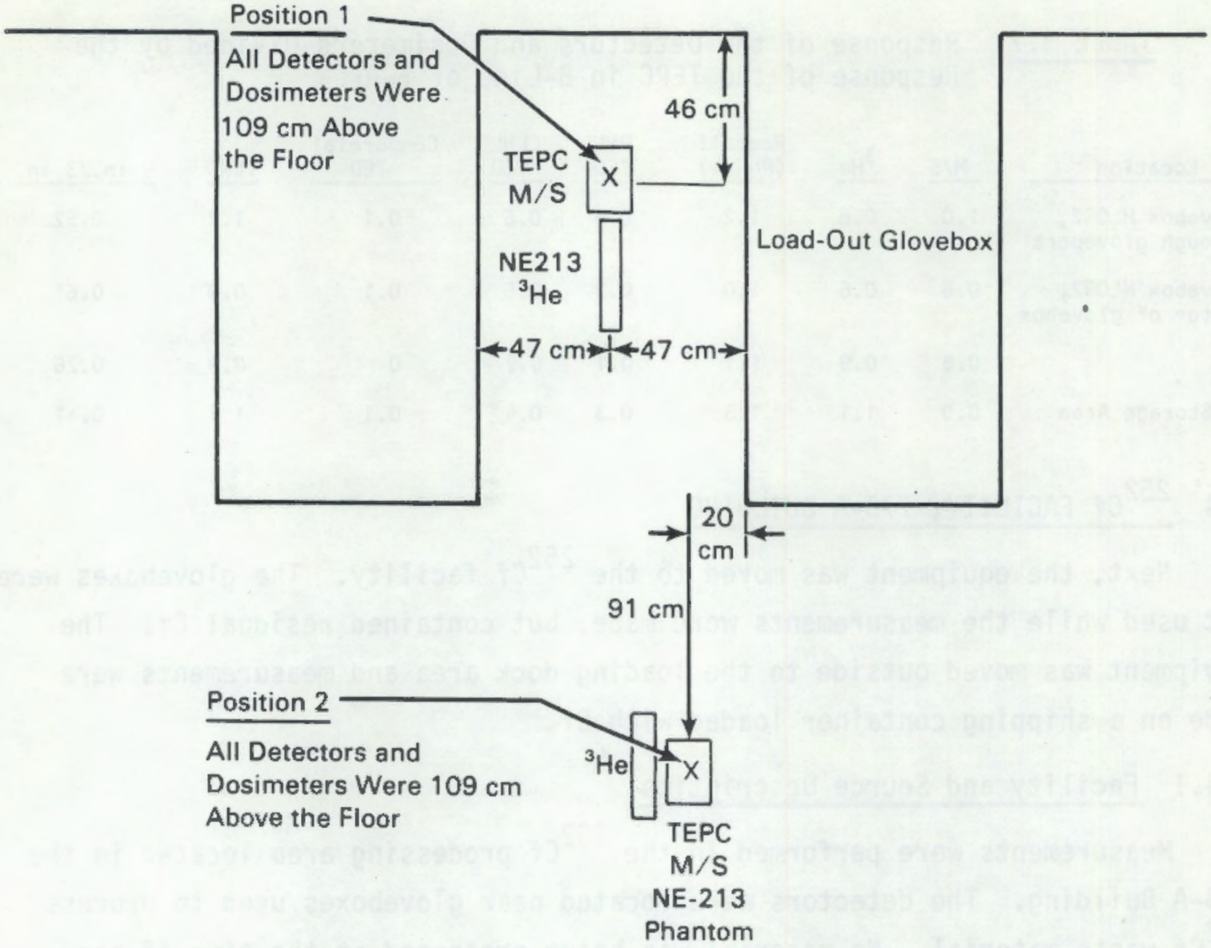


FIGURE 3.27. Measurement Locations in ^{252}Cf Facility in 773-A Building

chosen to allow placement of the detectors on a small ramp in the aisle. Because of the increased slant range, neutrons must pass through a considerable amount of shielding to reach Position 2. The dose rates changed rapidly with distance around the glovebox, and surveys were made with a Snoopy (serial number 5096) and an Eberline RO1S-1 (serial number 302) provided by SRP. At Position 1 the indicated dose equivalent rates were 170 mrem/h of neutrons and 11 mR/h of gammas; at Position 2 the rates were 50 mrem/h of neutrons and 2 mR/h of gammas.

The first measurements were made with the multisphere spectrometer, then the stand was removed and the remaining equipment placed into position. TEPC #501 was placed at Position 1 between the gloveboxes and the NE-213 spectrometer placed next to it. TEPC #184 was located at Position 2 and the ^{3}He spectrometer placed behind it. The TEPCs were left in place and the NE-213 and ^{3}He spectrometers reversed for the second set of measurements.

The final set of measurements was made next to a shipping cask containing 16 mg of ^{252}Cf as of 9/1/85. The detectors were positioned at 15 cm (6 in.) away from the cask and 109 cm (43 in.) above the floor as shown in Figure 3.28. It was assumed that the cask was symmetric for these measurements. The measurements were made overnight outside the building, and it is thought that temperature changes may have influenced the NE-213 spectrometer and TEPC #184.

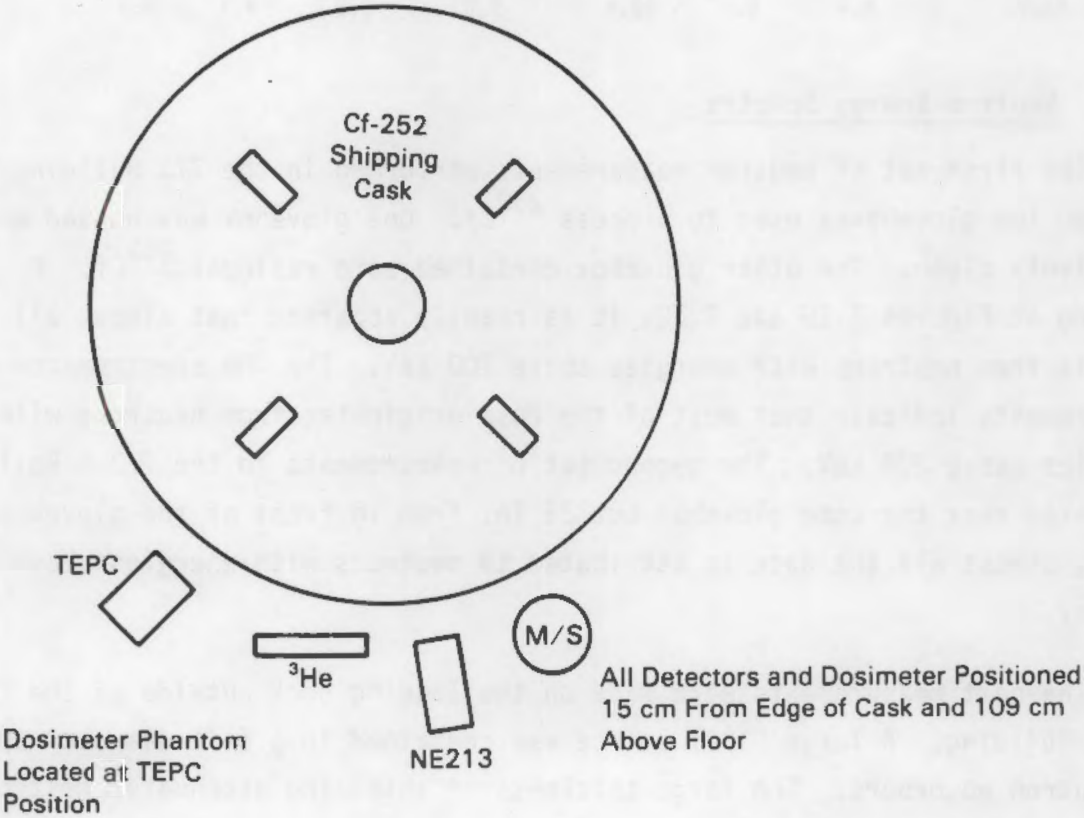


FIGURE 3.28. Measurement Location on Loading Dock of 773-A Building

3.4.3 Neutron Dose Equivalent Rates

Table 3.8 shows neutron dose equivalent rates at the ^{252}Cf facility in the 773-A Building.

TABLE 3.8. Neutron Dose Equivalent Rates (mrem/h) at the ^{252}Cf Facility in 773-A Building

Location	TEPC	M/S	^{3}He	Remball	PNL TED	LLNL TED	Commercial TED	TLND
18.5 in. from Glovebox	98.9	73.8	87.9	-	-	-	-	-
36 in. from Glovebox	40.1	25.9	23.8	37.7	16.9	21.4	8.4	32.2
Loading Dock	8.4	6.1	10.8	9.0	2.8	3.3	2.2	2.7

3.4.4 Neutron Energy Spectra

The first set of neutron measurements performed in the 773 Building was between two gloveboxes used to process ^{252}Cf. One glovebox was unused and relatively clean. The other glovebox contained some residual ^{252}Cf. By looking at Figures 3.29 and 3.30, it is readily apparent that almost all the dose is from neutrons with energies above 200 keV. The ^{3}He spectrometer measurements indicate that most of the dose originates from neutrons with energies above 200 keV. The second set of measurements in the 773-A Building was taken near the same glovebox but 36 in. from in front of the glovebox. Again, almost all the dose is attributed to neutrons with energies above about 500 keV.

The next measurements were made on the loading dock outside of the 773-A Building. A large ^{252}Cf source was contained in a 6-ft-diameter sphere of neutron absorbers. The large thickness of shielding attenuated most of the thermals and intermediate neutrons emitted from the source, leaving only fast neutrons reaching the detector. Figures 3.31 and 3.32 show mostly fast neutrons contributing to the dose. The thermal component observed was caused from the fast neutrons scattering from the walls or floor on the loading dock.

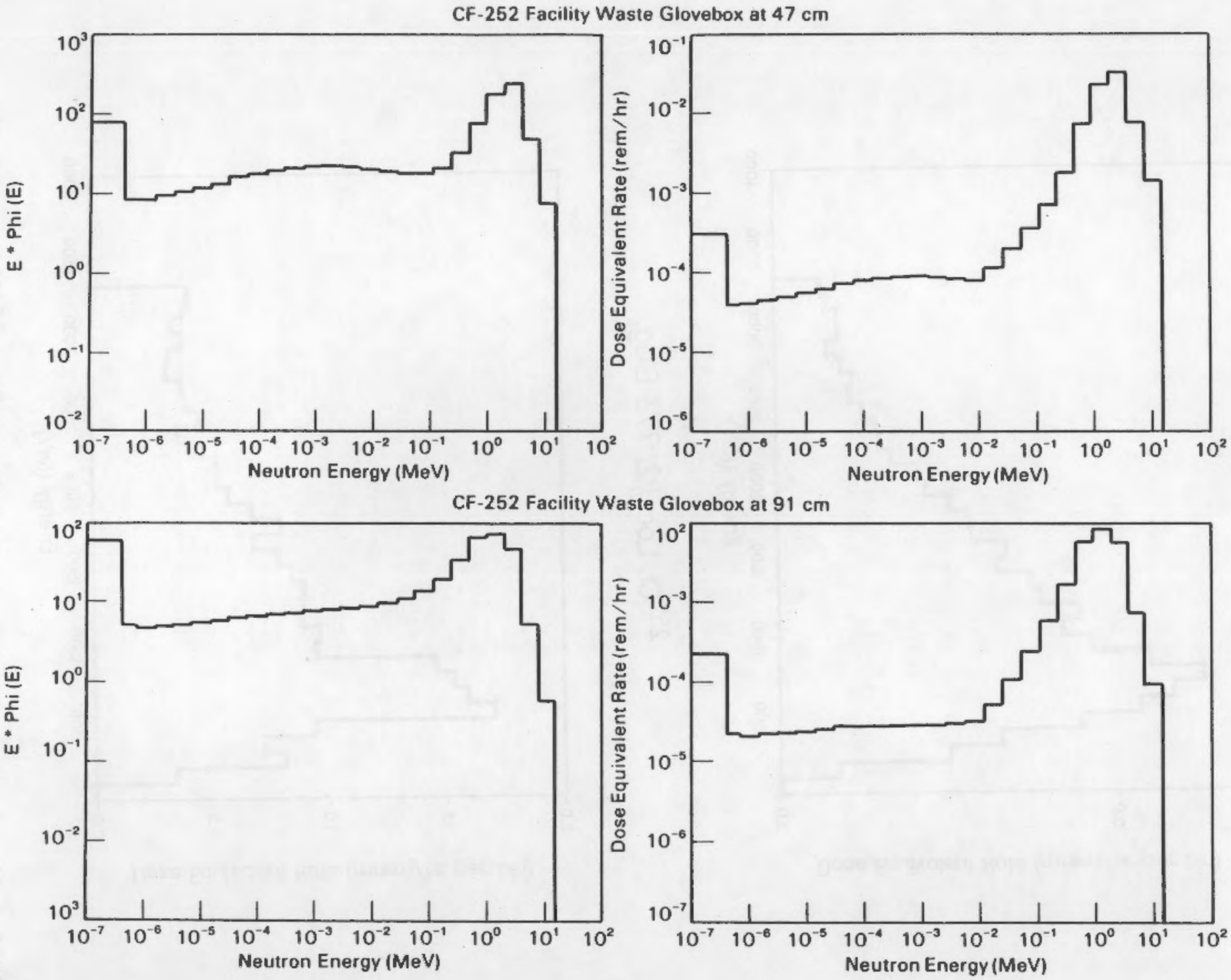


FIGURE 3.29. Neutron Energy Spectra Measured by the Multisphere Spectrometer Near the ^{252}Cf Waste Glovebox in 773-A Building

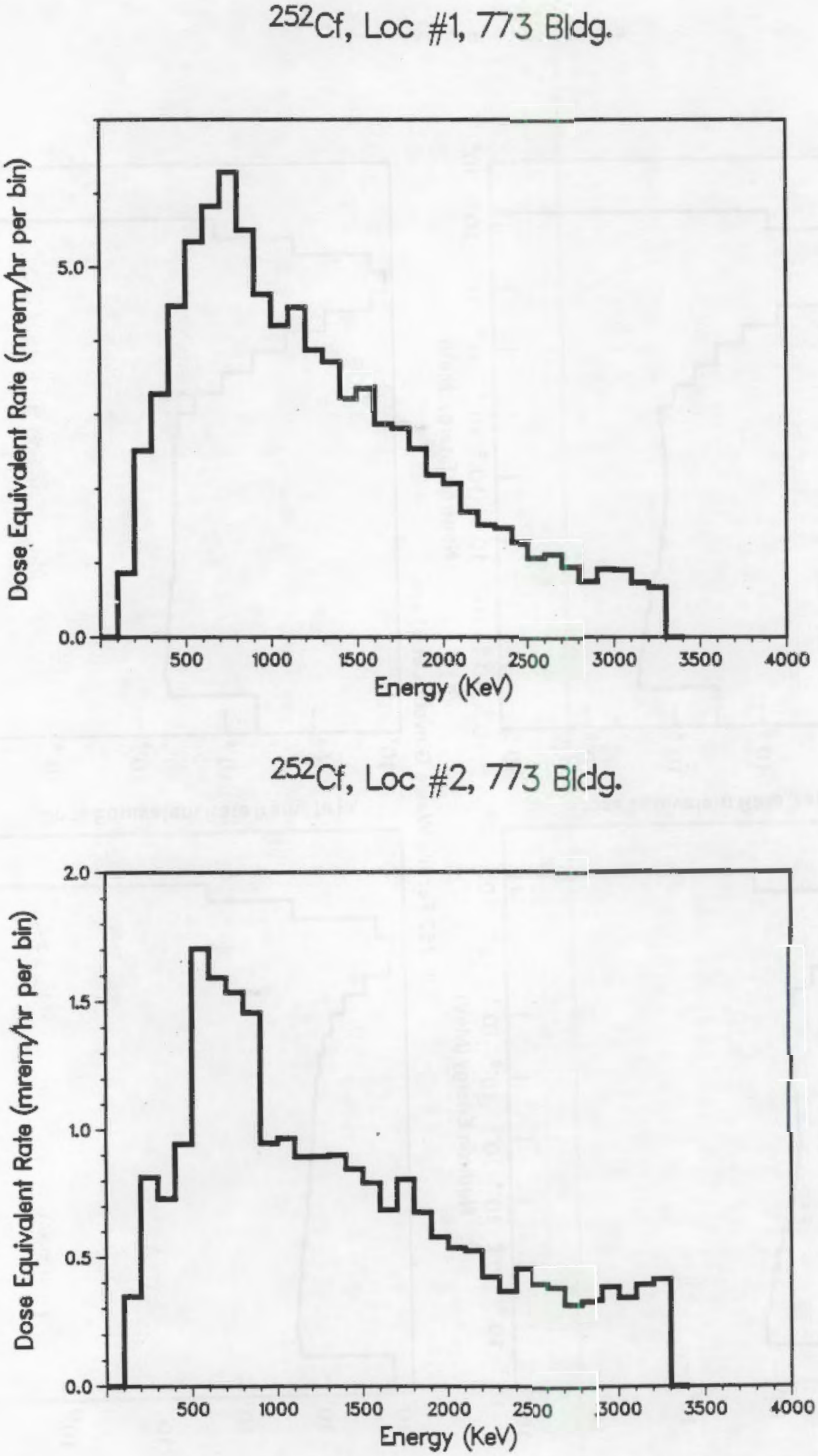


FIGURE 3.30. Neutron Dose Equivalent Rates Near ^{252}Cf Process Glovebox in 773-A Building Determined from Energy Spectra Measured by the ^{3}He Spectrometer

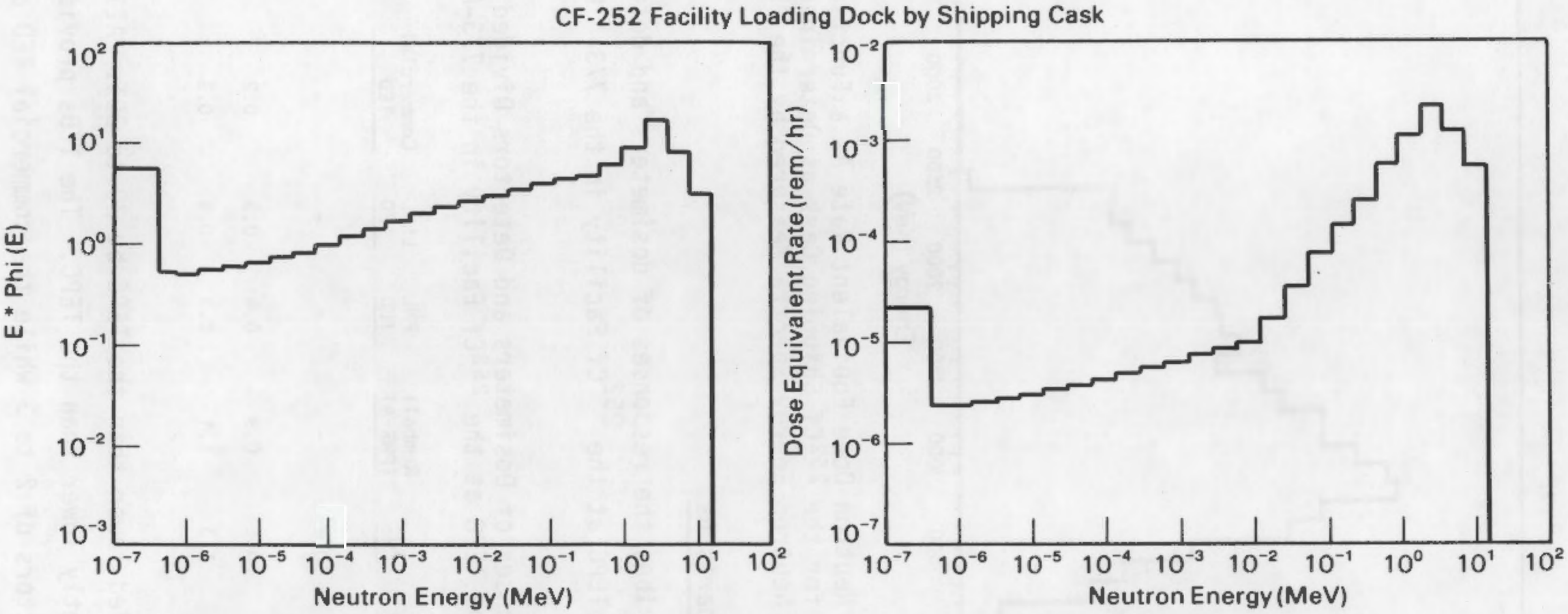


FIGURE 3.31 Neutron Energy Spectra Measured by the Multisphere Spectrometer Near ^{252}Cf Source in Shipping Cask

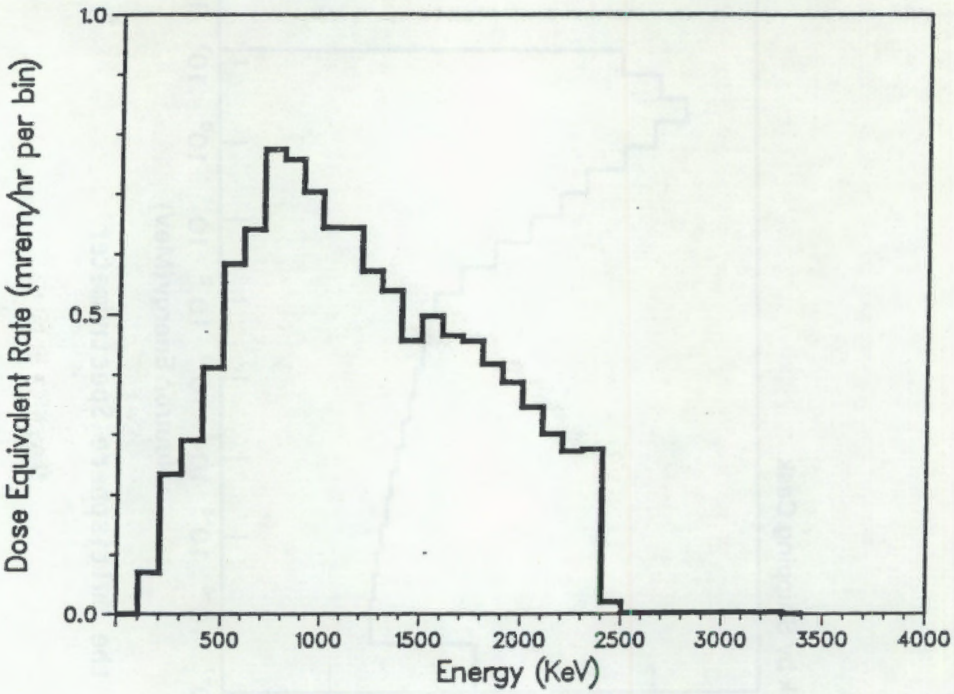


FIGURE 3.32. Neutron Dose Equivalent Rate As a Function of Energy for the ^{252}Cf Shipping Cask as Determined from the Neutron Energy Spectra Measured by the ^{3}He Spectrometer

3.4.5 Response Comparisons

Table 3.9 describes the responses of dosimeters and detectors divided by the response of the TEPC at the ^{252}Cf Facility in the 773-A Building.

TABLE 3.9. Responses of Dosimeters and Detectors Divided by the Response of the TEPC at the ^{252}Cf Facility in the 773-A Building

Location	M/S	^{3}He	Remball (PNR-4)	PNL TED	LLNL TED	Commercial TED	TLND	9 in./3 in.
18.5 in. from glovebox	0.8	0.9	-	-	-	-	-	-
36 in. from glovebox	0.7	0.6	0.9	0.4	0.5	0.2	0.8	0.51
Loading Dock	0.7	1.3	1.1	0.3	0.4	0.3	0.3	0.80

The M/S responded lower than the TEPC by 20 to 30%. All the dosimeters responded significantly lower than the TEPC. The TEDs provided by PNL and LLNL were low by factors of 2 to 3 while the commercial TED and TLND were low by factors of 2 to 5.

3.5 K-AREA REACTOR

After measurements were completed at the ^{252}Cf facility, the equipment was moved to the K-Area reactor. The final measurements were made here.

3.5.1 Facility and Source Descriptions

The last measurements was performed in K-Area in the reactor building. The reactor was operating at full power during the measurements.

3.5.2 Measurement Locations

The measurements were performed behind a thick steel shield door in the overhead crane wash area. A measurable neutron dose rate was present, and it is thought that these neutrons may be produced by photo-fission reactions produced by very high energy gamma rays (6 to 7 MeV) from ^{16}O in cooling water pumped from the reactor. During these measurements, one of the multichannel analyzers failed, so only a limited number of measurements were made. The detectors were positioned at a distance of 30 cm (1 ft) from the reactor wall near the center of the wall, as shown in Figure 3.33. The multisphere spectrometer was positioned opposite the radiation zone sign. All the detectors were

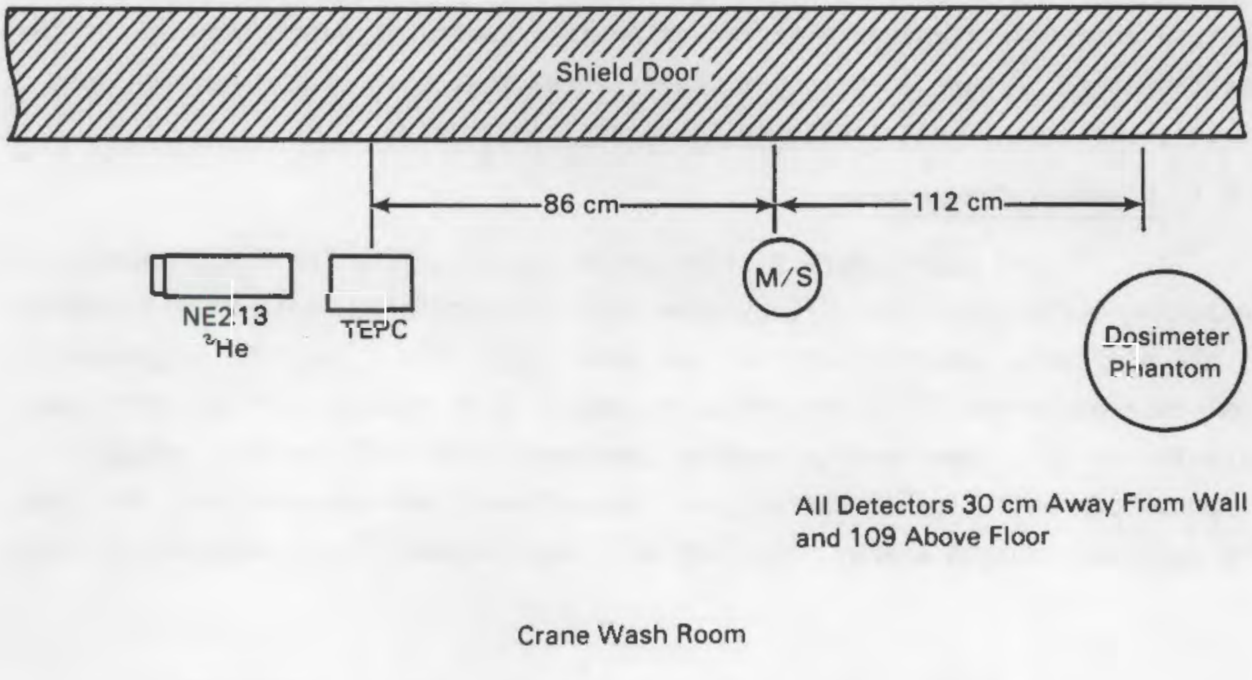


FIGURE 3.33. Measurement Locations in K-Reactor Facility

109 cm (43 in.) above the floor. The dose equivalent rate was measured to be 3.8 mrem/h using a PNR-4 supplied by the SRP. A quick survey indicated that the neutron dose equipment rates were nearly constant along the reactor shield door.

3.5.3 Neutron Dose Equivalent Rates

One set of measurements was made in K-Area behind the reactor shield door of K-Reactor. The results are seen in Table 3.10.

TABLE 3.10. Neutron Dose Equivalent Rates (mrem/h) at K-Reactor

TEPC	M/S	^{3}He	Remball	PNL TED	LLNL TED	Commercial TED	TLND	Gamma (Vic.-471)
2.0	2.2	5.2	3.5	0.4	1.0	0	6.8	2.5

3.5.4 Neutron Energy Spectra

The average neutron energy was 170 keV as measured by the multisphere spectrometer. This was the lowest average energy measured of all the locations. This was expected because of the large steel shield door, concrete walls, and distance from the reactor. Figure 3.34 shows the energy and dose spectra as measured by the multisphere spectrometer. Figure 3.35 shows the neutron dose equivalent as a factor of neutron energy as determined by the ^{3}He spectrometer. Figure 3.35 in particular shows that most of the neutron dose at this location is attributed to low-energy neutrons.

3.5.5 Response Comparisons

The TEPC and multisphere system agreed closely. The ^{3}He spectrometer responded higher than the TEPC by more than a factor of 3, most likely because of the extremely low dose rate and the poor statistics. The TEDs responded low compared to the TEPC; the albedo dosimeter TLND responded high, which was expected at this lower energy neutron spectrum. The TLND yields a higher response per unit flux at thermal and intermittent neutron energies. At this low dose and neutron energy, the TEDs will not respond to all neutrons. Since

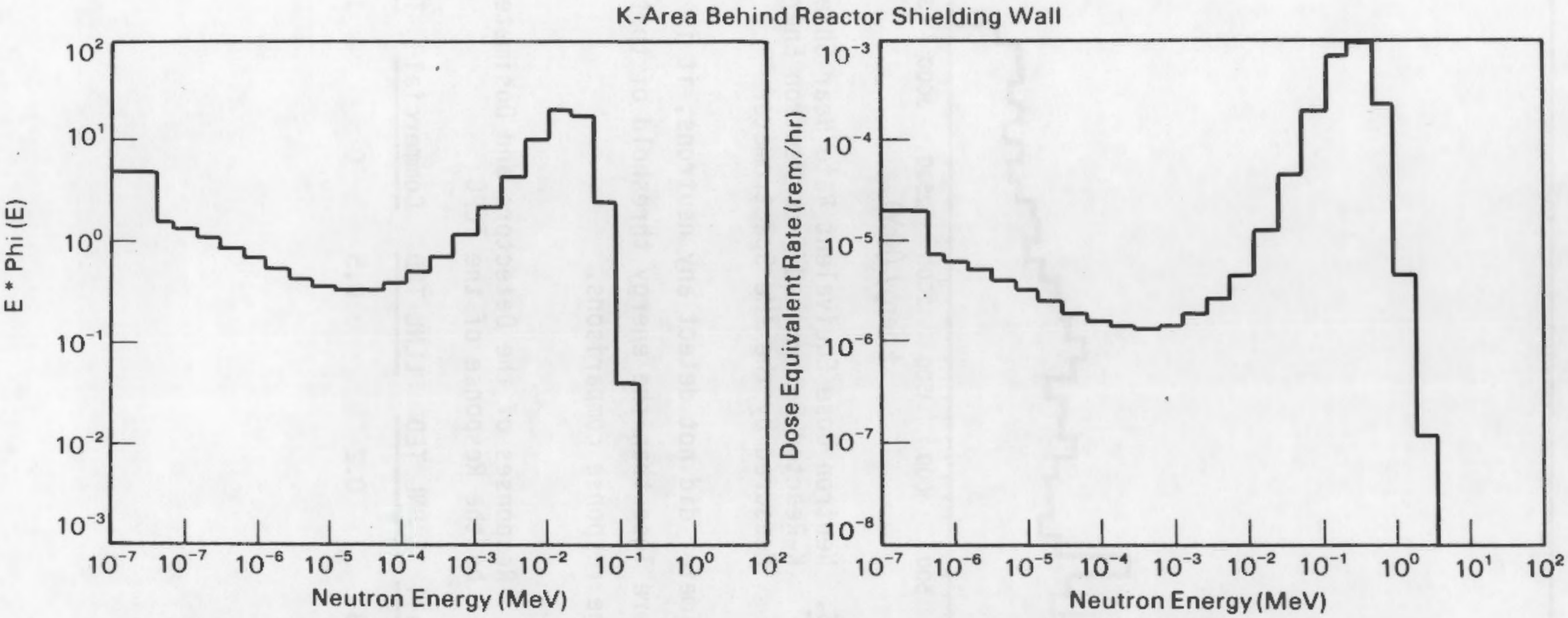


FIGURE 3.34. Neutron Energy Spectra Measured by the Multisphere Spectrometers at K-Reactor

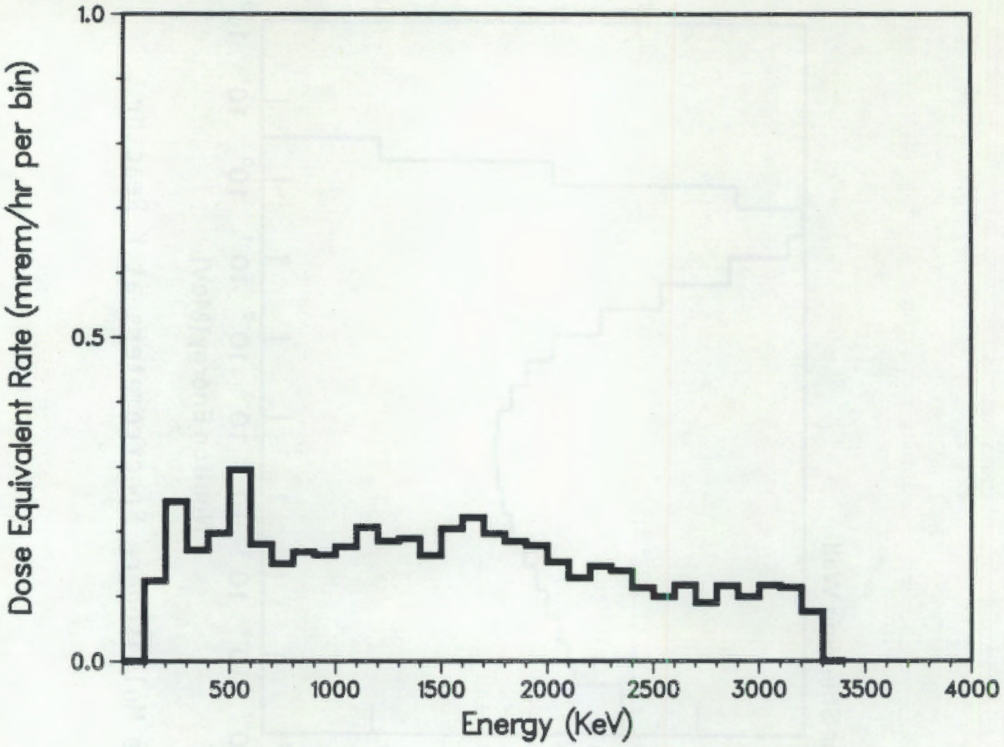


FIGURE 3.35. Neutron Dose Equivalent Rate Near Shield Door of K-Reactor Determined from Neutron Energy Spectra Measured by the ^{3}He Spectrometer

the commercial dosimeter did not detect any neutrons, it is assumed that the neutron energies were less than the energy threshold of that dosimeter. Table 3.11 shows the response comparisons.

TABLE 3.11. Responses of the Detectors and Dosimeters Divided by the Response of the TEPC

M/S	^{3}He	Remball	PNL TED	LLNL TED	Commercial	TLND	9 in./3 in.
1.1	2.6	1.8	0.2	0.5	0	3.4	0.23

4.0 DISCUSSION OF RESULTS

Before fully discussing the results, the limitations of the measurements and of each of the systems used are described. Problems encountered with the MCA and one of the TEPCs are discussed first, followed by a description of how the problems affected the accuracy of the measurements.

To ensure proper operation during the measurements at SRP, all the equipment was thoroughly checked by exposing the dosimeters and spectrometers to known doses of neutrons from a calibrated ^{252}Cf source at PNL. Since all the equipment was functioning perfectly, it was shipped to another DOE site for measurements. However, because of scheduling limitations, the equipment was then shipped directly to SRP for the measurements conducted in October 1985. During the measurements on the last day at the K-Reactor, problems were encountered with the multichannel analyzers. Upon return to PNL, all the equipment was again checked as part of normal laboratory procedures. It was subsequently discovered that two of the analog-to-digital converters (ADCs) used in the multichannel analyzer had failed. These ADCs had been used for some of the NE-213 spectrometer and ^{3}He spectrometer measurements. Since it is not known with certainty if the equipment was damaged during shipping or if it was working intermittently during the measurements at SRP, some of the results obtained in October 1985 with the NE-213 spectrometer should be viewed with caution. Just prior to the measurements in April 1986, the NE-213 system was checked with a ^{252}Cf source. At that time, the NE-213 scintillator was found to be inoperative. A new NE-213 scintillator was tested and taken to SRP for the measurements in April. This system operated perfectly during the April measurements.

The NE-213 scintillation detector is sensitive to both neutrons and gamma rays. Gamma-ray interactions produce scintillation pulses that have a slightly faster risetime than that of neutron pulses. Thus, gamma- and neutron-induced events can be separated on the basis of risetime by the Link Systems 5010 Pulse Shape Discriminator. Unfortunately, the discrimination is not perfect, and there is some crossover between the neutron and gamma channels. This is especially true at lower energies. It is difficult to distinguish between neutron and gamma events below about 1.2 MeV, which is the lower limit of energy response for the NE-213 spectrometer.

The NE-213 spectrometer functions well in mixed fields where there is a high neutron-to-gamma ratio, such as those found in the calibration facility and the californium encapsulation facility. It does not function well in areas where there is a high gamma-to-neutron ratio, such as areas with massive neutron shielding with little gamma shielding found around gloveboxes with thick acrylic plastic shields.

The crossover problem is further complicated at high gamma exposure rates. At gamma exposure rates of tens to hundreds of mR/h, there is considerable gamma pulse pile-up. This results in overlapping pulses which have slower apparent risetimes and are mistaken for neutron pulses. This occurred in the measurements made in front of open gloveports, where there is an abundance of low-energy photons from ^{241}Am and K and L x-rays from plutonium and americium contamination on the interior surface of the glovebox.

In retrospect, it would have been preferable to have shielded the NE-213 detector with lead gamma shielding, although this tends to distort the spectrum measurement. Lead shielding was used during the measurements in the calibration facility in April 1986. It would have been preferable to reduce the number of measurements and to make longer measurements in lower exposure rates. This was not possible because it would have interfered with work schedules in production facilities.

Although measurements were taken with the NE-213 spectrometer at every measurement location, not all the results are included in this report. It is possible to obtain an idea if there are gamma crossover or pulse pile-up problems by comparing the dose equivalent rates calculated from the NE-213 spectrometer measurements with other measurement. Thus, only the NE-213 spectrometer measurement that provided approximately correct dose equivalent rates were included in this report. This includes all the measurements in the calibration and ^{252}Cf facilities, but only a few from the H and F areas.

The ^{3}He spectrometer was used to measure neutrons with energies from 100 keV to 5 MeV. Although ^{3}He spectrometer measurements were taken at every measurement location, only the neutron flux versus energy graphs for the calibration sources are included in this report. However, the neutron dose equivalent rate graphs as determined by the ^{3}He spectrometer at every measurement location were included since the ^{3}He spectrometr yielded better resolutions in the 100 keV to 5 MeV range.

The multisphere analysis code determines the neutron flux density in 26 logarithmic energy bins extending from thermal energies to 20 MeV. This is determined from measurements with only seven detector configurations. The analysis code thus solves for 26 unknown fluxes with only seven known responses; this is a mathematically under-defined problem and no unique solution can exist. In fact, there are an infinite number of linked solutions mathematically possible. The SPUNIT analysis code (Brackenbush 1984) uses an analysis technique based on information theory, which is supposed to give the most probable flux. However, it has been demonstrated (Scherpelz and Brackenbush 1985) that because of the nature of the response functions used for the 3- and 5-in. detectors, there can be significant variations in the intermediate energy fluxes calculated by the analysis code. The integral quantities (total flux and dose equivalent rates) are calculated accurately, but there can be uncertainties in the differential flux at intermediate energies.

4.1 ANALYSIS OF RESULTS FOR THE CALIBRATION FACILITY

As expected, there is good agreement between the various dosimeters and spectrometer measurements at the SRP calibration facility. Using the values measured by the TEPC as a reference, there is excellent agreement between the dose equivalent values measured by the TEPC and those calculated from the multisphere spectrometer and ^{3}He spectrometer, as shown in Table 3.2. The agreement is within 10%, except for the measurement for the PuBe source with no D_2O moderator, where the multisphere gives a value 18% lower. The SRP calculated dose equivalent rate of 11.9 mrem/h, which was calculated by Hoy (1980), is 18% less than the TEPC measured value of 14.5 mrem/h. This agreement is acceptable considering that the SRP value is calculated from spectrum measurements and the TEPC measurement derives dose and quality factors directly without any reference to the neutron energy spectrum. The agreement is about the same for the PuBe source. The SRP calculated dose equivalent rate for the 0-mm D_2O position is 34.2 mrem/h, which is 18% less than the TEPC measured value of 41.8 mrem/h. (Note: There is almost exact agreement between the multisphere measurement and the SRP value.) The SRP calculated dose equivalent for the 150-mm D_2O position is 12.3 mrem/h, which is 50% higher than the TEPC measurement of 8.2 mrem/h. The multisphere measured value of 8.1 mrem/h agrees closely with the TEPC measurement.

In general, the passive dosimeter measurements agree reasonably well, as was shown in Table 3.5. The PNL and LLNL CR-39 TEDs are in good agreement, but the commercial TED is significantly lower by about an average of 50%.

The spectral measurements made with the multisphere spectrometer and NE-213 spectrometer are in good agreement. There may be some gamma cross-over for the PuF_4 measurement with the NE-213 spectrometer, but the spectrum presented in Figure 3.11 is in excellent agreement with that shown in Figure 3.12, which is the result of an earlier measurement on a similar source at PNL taken with ^{6}Li and ^{3}He sandwich spectrometers (Brackenbush and Faust 1970). The multisphere spectrometer lacks resolution at higher neutron energies, but generally shows few neutrons above 3 MeV in agreement with the NE-213 spectrometer measurements. The measurements for the PuBe source indicate neutrons with energies to 10 MeV, as expected from other measurements with PuBe sources. The NE-213 spectrometer data exhibit quite a bit of scatter, but are in general agreement with measurements made with bare PuBe sources. However, the D_2O moderator seems to eliminate some of the peak and valley structure present in the bare sources. The multisphere spectrometer also indicates a significant number of fast neutrons with energies up to 10 MeV.

4.2 H- AND F-AREA B-LINES

The B-Lines in the H- and F-Areas are plutonium production lines. The H-Area facility was being renovated and contained no loose contamination. The only source of neutrons was the $^{238}PuO_2$ in EP-61 containers placed in the hoods and gloveboxes for these measurements. The F-Area was actually processing plutonium during the measurements, and it was difficult to define the neutron source because of the large amounts of residual plutonium in the gloveboxes and process lines. To minimize the impact of the measurements on production schedules, several measurements were taken simultaneously. This introduced some positioning error, since the neutron fields varied considerably with position.

For the H-Area measurements on the $^{238}PuO_2$ and ^3He sources, there was relatively good agreement between the TEPC, ^3He, and multisphere measurements for the dose equivalent rate. The values agreed within 7 to 15%, except behind the glovebox in Room 514 where the dose rate was extremely low, so it is reasonably certain the measured values are correct. However, there was some gamma crossover in the NE-213 spectrometer at these locations.

The passive dosimeter results for the H-Area show considerably more scatter. The TLND and commercial TEDs registered only a fraction (0.3 to 0.5) of the dose equivalent rate indicated by the TEPC, which is assumed to measure the true dose equivalent rate. This could be attributed to the PuO_2 having a harder neutron energy spectrum (2.3 MeV average) than the PuF_4 calibration source (1.4 MeV average). Surprisingly, the TEDs supplied by both PNL and LLNL overestimated the dose equivalent rate by a factor of from 1.0 to 2.7.

The measurements at F-Area B-Line showed considerably more scatter. The TEPC and multisphere measured dose equivalent rates agreed within 5 and 8% for the measurements made with TEPC 501. However, the TEPC and multisphere measurements agreed within 23% for the measurements made with TEPC 184. This is the TEPC that is suspected of experiencing gain shifts during the measurements. Thus, the TEPC measurement for the MLOR2 glovebox between the gloveports and for the POR may be too high. The ^3He spectrometer measurements agreed with the TEPC in the POR and vault area. The ^3He spectrometer results were lower than the TEPC near the glovebox but this was probably because of different positioning of the detector and a high dose rate gradient.

The TLND measurements were about 20% less than the TEPC results, except for the two locations where the TEPC data is suspect. At these two locations, the TLND was about 10% lower than the TEPC. The TEDs only measured a fraction (0.1 to 0.6) of the TEPC-measured dose equivalents. This is probably because of the lower energy spectrum resulting from the neutron shielding added to the gloveboxes. Also, the passive dosimeters were placed on a phantom that was farther away from the glovebox in a somewhat lower dose equivalent rate. This was unavoidable because of the time constraints.

4.3 ^{252}Cf FACILITY AND K-REACTOR

Surprisingly, in the ^{252}Cf facility in the 773 Building the dose equivalent rates measured by the multisphere spectrometer were 25 to 35% lower than those measured by the TEPC. Two of the measurements (at 27 and 35%) were made with TEPC #184 and are suspect because of possible gain shifts during the measurements. However, the ^{3}He spectrometer data tend to support the TEPC measurements. The dose equivalent rate calculated from the neutron spectra from the ^{3}He spectrometer is 11% lower than the TEPC measured value 18 in. from the glovebox. The gamma-to-neutron ratios are low around the glovebox, so there is little gamma crossover. The NE-213 spectra supported the ^{3}He and TEPC measurements.

The results obtained with the passive neutron dosimeters were not expected. The TEDs supplied by PNL and LLNL indicated dose equivalent rates that were factors of 2 to 3 times lower than the TEPC and multisphere measurements. The commercial and TLND dosimeter results were factors of 2 to 5 times lower than the TEPC and multisphere measured values. The passive dosimeter measurements were made after the spectrometers were removed, and it is possible that there could be some positioning error, but this would not explain the wide variations observed between the passive dosimeter results and the TEPC and multisphere measured results.

The results obtained at K-Reactor are as expected. The TEPC and multisphere agree within 10%. Both the multisphere and ^{3}He spectrometers indicate a soft neutron spectrum behind the reactor shield door. The TLND over estimates the dose equivalent rate by a factor of 3.2, while the commercial dosimeter failed to measure any neutrons. The PNL and LLNL track etch dosimeters only measured a fraction (0.2 to 0.5) of the TEPC measured value. All these measurements indicate a very soft spectrum with the majority of neutrons having energies below 1 MeV.

4.4 SUMMARY OF MEASUREMENTS

Neutron dose and energy spectral measurements were conducted at the SRP in October 1985 and April 1986. The October 1985 measurements were taken in the following areas and buildings: the B-Line of 221-H, the calibration rooms in 736A, the B-Line of 221-F, the ^{252}Cf processing area in 773-A, and outside the reactor shield door in the crane wash area of K-Reactor. The April 1986 measurements were all taken in the calibration rooms of 736-A. Table 4.1 summarizes the measured neutron dose equivalent rates in mrem/h at all the measurements locations. Table 4.2 shows the response comparisons between the TEPC and the other instruments and dosimeters.

There was generally good agreement between the TEPC and multisphere measurements. The values agreed within 5 to 35%. Since the TEPC and multisphere spectrometer determine dose equivalent by completely different techniques, the authors believe that the TEPC-measured dose equivalent rates represent nearly correct values. The passive dosimeter results can be compared with the TEPC and multisphere measurements to obtain an idea of how the dosimeters respond to different neutron energy spectra in work locations. In the very soft spectra found at K-Reactor, the TLND used by SRP overestimated dose equivalent by a factor of 3.4. In some work locations, such as the H-Area plutonium processing line, the TLND underestimated dose equivalent by a factor of 1.5 to 2.5. As expected, the passive TEDs indicated the correct dose equivalent in hard spectra, such as those found in the calibration facility for the PuF_4 source, but only measured a small fraction of the correct dose equivalent in soft spectra, such as the K-Reactor spectra. This is because of the threshold at about 200 keV for the CR-39 track etch material used.

TABLE 4.1. Neutron Dose Equivalent Rates (mrem/h) at Selected Locations Inside the Savannah River Plant

	Instruments				Dosimeters			
	TEPC	M/S	^{3}He	PNR-4	PNL TED	LLNL TED	Commercial TED	TLND
736-A Building								
PuF_4 with drum	14.5	12.7	-	16.2	12.7	16.4	4.4	9.3
PuF_4 without drum	14.5	12.6	15.2	16.0	17.8	16.7	4.7	9.5
PuBe at 0 mm	41.8	34.4	38.8	46.6	41.2	35.8	28.6	32.0
PuBe at 150 mm	8.2	8.1	8.5	10.7	7.3	6.7	4.7	13.0
221-H Building								
Front of hood #1	21.1	19.4	17.8	27.0	18.7	20.2	6.2	8.6
Behind Glovebox #4	0.9	0.8	1.4	1.0	2.4	1.2	0	1.0
Front of Glovebox #4	5.2	6.0	6.6	7.5	-	-	-	-
Through gloveport of Glovebox #4	15.1	14.2	12.4	19.5	15.7	28.0	3.8	11.6
221-F Building								
MLOR2 through gloveport	33.4	31.8	19.7	40	12.0	20.5	4.3	40.3
MLOR2 through center	47.8	37.0	27.3	47	15.0	26.5	6.7	42.3
POR	4.0	3.1	3.6	4.4	0.5	0.7	0	2.6
Plutonium storage area	15.7	14.5	16.9	21	4.6	6.9	2.0	20.6
773-A Builidng								
18.5 in. from glovebox	98.9	73.8	87.9	-	-	-	-	-
36 in. from glovebox	40.1	25.9	23.8	37.7	16.9	21.4	8.4	32.2
Loading dock	8.4	6.1	10.8	9.0	2.8	3.3	2.2	2.7
K-Reactor								
Reactor shield door	2.0	2.2	5.2	3.5	0.4	1.0	0	6.8

TABLE 4.2. Response Comparison of Instruments and Dosimeters Normalized to the TEPC

	Instruments			Dosimeters			
	M/S	^{3}He	PNR-4	PNL TED	LLNL TED	Commercial TED	TLND
736-A Building							
PuF$_4$ with drum	0.9	-	1.1	0.9	1.1	0.3	1.0
PuF$_4$ without drum	0.9	1.0	1.1	1.2	1.2	0.3	1.0
PuBe at 0 mm	0.8	1.1	1.1	1.0	0.9	0.7	1.2
PuBe at 150 mm	1.0	1.0	1.3	0.9	0.8	0.6	2.5
221-H Building							
Front of hood #1	0.9	0.8	1.3	0.9	1.0	0.3	0.4
Behind Glovebox #4	0.9	1.6	1.1	2.7	1.3	0	1.1
Front of Glovebox #4	1.2	1.3	1.4	-	-	-	-
Through gloveport of Glovebox #4	0.9	0.8	1.3	1.0	1.9	0.3	0.8
221-F Building							
MLOR2 through gloveport	1.0	0.6	1.2	0.4	0.6	0.1	1.2
MLOR2 through center	0.8	0.6	1.0	0.3	0.6	0.1	0.9
POR	0.8	0.9	1.1	0.1	0.2	0	0.9
Plutonium storage area	0.9	1.1	1.3	0.3	0.4	0.1	1.3
773-A Builidng							
18.5 in. from glovebox	0.8	0.9	-	-	-	-	-
36 in. from glovebox	0.7	0.6	0.9	0.4	0.5	0.2	0.8
Loading dock	0.7	1.3	1.1	0.3	0.4	0.3	0.3
K-Reactor							
Reactor shield door	1.1	2.6	1.8	0.2	0.5	0	3.4

5.0 CONCLUSIONS AND RECOMMENDATIONS

The neutron dose equivalent rates measured by the TEPC agreed well with the values calculated from the neutron fluxes measured by the multisphere and ^{3}He spectrometers at almost every measurement location. In addition, the TEPC and spectrometers measured values agreed with the dose equivalent rates calculated from previous spectrometer measurements for the SRP calibration sources. In view of the good agreement obtained by completely different techniques, we conclude that these devices provided accurate measurements of the actual neutron dose equivalent. Although the NE-213 spectrometer did not cover the entire energy range of neutrons present at the measurement locations, it confirmed the spectra measured by the multisphere and ^{3}He spectrometers and provided better resolved spectra above 1.2 MeV.

The spectral measurements showed that there are wide variations in the neutron energy spectra at work locations at SRP. Since all TLD-albedo dosimeters, including the TLND used at SRP, are highly energy dependent, the differences observed for the dose equivalent rates estimated by the TLND and those measured by the TEPC and multisphere spectrometer are not surprising. Differences of factors of two were observed at SRP, and even larger differences have been observed elsewhere. For instance, at commercial nuclear power reactors, TLD-albedo dosimeters can overestimate neutron dose equivalent by a factor of 20 (Endres et al. 1981).

The International Commission on Radiological Protection (ICRP) has already recommended that the quality factor for fast neutrons be increased from the present value of 10 to a new value of 20 (ICRP 1985). It is expected that these recommendations may be adopted by DOE in the future, which will result in increasing the neutron dose equivalent rates by almost a factor of two at most of the work locations at SRP. In some instances, the neutron dose equivalent will be a significant fraction of the worker's total dose. It will be necessary to increase the accuracy of the neutron dosimetry system in the future.

The following recommendations are presented as possible methods to increase the accuracy of the neutron dosimeters used at SRP:

- Neutron calibration sources used at SRP should be better characterized.

  The neutron calibration sources used at SRP are unique, and their spectra are not directly comparable to any other neutron sources currently in use. The PuF_4 calibration source is a mixture of PuF_4 and PuO_2, but most of the neutrons emitted by the source originate from $F(\alpha,n)$ reactions, as seen by the ^3He spectrometer and ^6Li sandwich spectrometer measurements. The PuBe neutron source with the D_2O moderator/reflector appears to be a unique calibration source, and it is difficult to make really accurate spectra measurements because of the number of intermediate energy neutrons produced by the moderator. Perhaps the dose equivalent rates could be more accurately defined with additional measurements and by Monte Carlo computer code calculations, which would include the effects of scatter by the D_2O and by the room.

- The uncertainty in the neutron emission rate from the PuBe source should be resolved.

  When new, similar PuBe sources at Hanford had 1.5 to 2% annual increases in their measured emission rate (DePangher and Nichols 1966) because of the decay of ^{241}Pu (a beta emitter) into ^{241}Am (an alpha emitter). The dose equivalent rates listed in Hoy (1980) were determined in 1970; so some increase in neutron emission rates and dose equivalent rates has undoubtedly occurred. If additional information about the isotopic composition of and date of separation of the plutonium is available, it may be possible to calculate the increase in neutron emission rate.

- Room scatter in the calibration facility should be characterized.

  In the future it may be desirable to perform dosimeter irradiation at distances other than the 81-cm distance presently used to comply with American National Standards Institute (ANSI) and Department of

Energy Laboratory Accreditation Program (DOELAP) procedures. The amount of room scatter will be different, and this will affect the response of TLD-albedo dosimeters and neutron survey instruments. The amount of room scatter and how it affects each device can be determined by performing inverse square measurements by exposing the device at different distances from the source. The analysis technique is explained in DePangher and Nichols (1966) and Schwartz and Eisenhauer (1982). It is recommended that inverse square measurements be made with the TLND, with moderator-based instruments used at SRP, and with TEPCs. Both the TLND and survey instruments will overestimate dose equivalent from the scattered neutrons from room return.

- Investigate the possibility of determining energy correction factors for the TLND used at SRP.

  One method of increasing the accuracy of the interpretation of the dose equivalent from the TLND is to characterize its response in actual work locations. The TEPC and spectrometer measurements performed at specific work locations by PNL can be compared with the TLND measurements at the same locations. This can be used as the basis for energy correction factors for specific facilities or jobs if desired. Additional measurements should be made with portable survey instruments, 9-in. to 3-in. sphere response ratio measurement, and TLND exposed on phantoms to determine the variability of the TLND dosimeter responses at various work locations in a facility.

- Investigate the possibility of using a combination neutron dosimeter.

  The TLD-albedo dosimeter has almost constant response below about 10 keV, but the response per rem decreases with increasing neutron energies for higher neutron energies. The CR-39 TED is insensitive to neutrons with energies below about 200 keV, but is sensitive to higher energy neutrons. The combination of a TLD-albedo with a TED provides a crude neutron energy spectrometer to increase the accuracy of the dose equivalent interpretation. Savannah River Plant personnel should investigate the possibility of adding CR-39 plastic detectors to the TLND to reduce the energy sensitivity and improve the accuracy of the neutron dosimeter.

- Use active instrumentation

  Recently there have been several active neutron instruments developed, such as the pocket remmeter developed by EG&G/Santa Barbara and the total dose meter developed jointly by PNL and EG&G/Santa Barbara. These instruments are based on TEPCs. In situations with unusual neutron energy spectra, these instruments may provide a better estimate of dose equivalent than TLD-albedo dosimeters. Also, the algorithms in the microprocessor of these instruments can be changed to account for charges in quality factor for fast neutrons, which may be instituted in the future.

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