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**Improvements in Apparatus and Procedures
for Using an Organic Liquid Scintillator
as a Fast-Neutron Spectrometer for
Radiation Protection Applications**

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May 15, 1987

**Lawrence
Livermore
National
Laboratory**

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IMPROVEMENTS IN APPARATUS AND PROCEDURES
FOR USING AN ORGANIC LIQUID SCINTILLATOR
AS A FAST-NEUTRON SPECTROMETER FOR
RADIATION PROTECTION APPLICATIONS

ABSTRACT

For use in radiation protection measurements, a neutron spectrometer must have a wide energy range, good sensitivity, medium resolution, and ease of taking and reducing data. No single spectrometer meets all of these requirements. For measurements over the energy range from 0.5 to 20 MeV, we selected a liquid organic scintillator. We conducted several experiments aimed at both improving the detector and characterizing its response to gamma rays and neutrons. One series of measurements showed that a light pipe was needed between the scintillator cell and the photomultiplier tube to achieve the best resolution. We found that 25 mm was the optimum length for the light pipe. Another experiment measured the light output of the scintillator as a function of gamma-ray energy. We found that light output was a linear function of electron energy above 100 keV, but it was nonlinear below that energy. Three experiments were conducted to determine the light output as a function of neutron energy. The three experiments gave consistent results, but, below 1 MeV, our light-output values do not agree with values available from the literature. Monte Carlo calculations were made to evaluate the effects of multiple neutron scattering and edge effects in the detector. The resulting correction factors were not completely adequate.

We also improved the electronic systems associated with the detector. A transistorized circuit was developed to provide the bias voltage for the photomultiplier tube dynodes. This circuit was needed to obtain pulse-height linearity over the wide range of signal sizes. We built a special live-time clock to compensate for the large amount of dead time generated by the pulse-shape discrimination circuit we chose to use.

We wrote new data reduction programs for small computers to allow data reduction in the field. One program extracts the information from the gamma-ray gain-calibration data using the measured gamma-ray light-output data. The program we developed to reduce the neutron data uses the output of the gamma calibration program, in combination with the neutron light-output

data, to rebin the raw data into bins of equal proton-energy width. The results are then differentiated to obtain the spectrum. This procedure allows parameters, such as efficiency, to be entered as data files rather than having to be calculated for each set of neutron data. Results obtained with this program were essentially identical with those from an earlier version that differentiated before rebinning.

Spectra measured with this system agree reasonably well with existing measured or theoretical spectra. The largest remaining difficulties occur below 2 MeV where multiple neutron scattering in the detector becomes significant. Additional work is needed to improve the corrections used for this distortion. More efforts are also needed to increase the portability of the system and increase its ease of operation.

1. INTRODUCTION

A decade of futile searches followed Rutherford's postulation of the existence of the neutron in 1920.¹ Then in 1930 a series of rapid advances began when Bothe and Becker found that alpha particles reacted with Li, Be, or B targets to produce a highly penetrating radiation.² This was substantiated by Curie in 1931.³ In 1932 Curie and Joliet reported that this penetrating radiation produced protons from hydrogenous absorbers. These were the first recoil proton measurements.⁴ That same year Chadwick identified the neutron by using an apparatus that measured the energies of recoil protons and other ions. His apparatus was the first neutron spectrometer.⁵

There are many ways to produce neutrons. Most facilities that use neutrons have modern versions of the alpha,n sources that were used by Chadwick. Less widely used are gamma,n (photo neutron) sources for which the gamma rays can complicate the neutron measurements. Another widely used neutron source is the spontaneous fission that occurs in heavy isotopes such as ²⁵²Cf. Uranium and many transuranic elements fission spontaneously and can be a significant source of neutrons. At Lawrence Livermore National Laboratory (LLNL), we have a variety of alpha,n and spontaneous fission sources including those in use at the Hazards Control Standards and

Calibration Laboratory.⁶ The neutrons produced by these sources can have energies that range from thermal (0.025 MeV) to 20 MeV.

Accelerators form another diverse group of neutron sources. Cockroft and Walton reported nuclear reactions induced by laboratory-accelerated particles in 1932, the same year the neutron was identified.⁷ Accelerator-produced neutrons can have energies of hundreds of MeV, but they may also reach thermal energies outside the shields. Electron accelerators and high energy x-ray sources can produce photo neutrons either intentionally or unintentionally. This is another case in which neutron measurements are complicated by a large photon component. The pulsed operation of many accelerators can also cause measurement problems. A wide variety of accelerators at LLNL produce neutrons. These include multi-use facilities like the Cyclograff and the electron linear accelerator, dedicated units like the rotating target neutron source, and high energy x-ray sources, such as those in use at Site 300.

Currently, fusion experiments do not produce large numbers of neutrons, but that will change as the technology develops. The radiation field outside of the shielding of a fusion reactor can include neutrons with energies from thermal to near 15 MeV. Several magnetic confinement and inertial confinement fusion experiments are being conducted at LLNL.

Fission reactors are prolific sources of neutrons with energies from thermal to over 10 MeV. Such reactors probably account for most of the neutron radiation to which people are exposed. At present, however, none are in operation at LLNL.

The need to include spectrometric measurements in a complete neutron dosimetry program is generally accepted.⁸ Dosimeters often are not sensitive over the entire range of energies that need to be measured, or they may not have the correct response per fluence at all energies. Calculations based on spectra can produce high quality dosimetric information, but making and interpreting spectrum measurements is more difficult than using other dosimetric methods. It is more practical to use a measured spectrum to make corrections to dosimeter data. This is reasonable as long as the spectrum does not change, which is the case for the fields outside the shielding of a reactor or an accelerator running without significant changes in the operating parameters. Spectrum measurements can also provide valuable information about the fields produced at a calibration facility.

Spectrometry can also confirm shielding calculations or provide input information for the calculations. This application requires considerable detail in the spectral data. In effect these measurements constitute cross-section verifications and, thus, must be able to resolve the details inherent in the cross sections.

To be useful for radiation protection, a spectrometer must be sensitive enough to provide usable data within a reasonable time, even in low intensity neutron fields. A 1 mrem-per-hour field is approximately 30 neutrons per square centimeter per second. Distributed uniformly throughout a spectrum ranging from thermal to 10 MeV, this is only 3 neutrons per square centimeter per MeV per second. Conversely, dosimetric measurements may be made in relatively intense fields, so the ideal spectrometer must also operate correctly at high count rates. Dose equivalent rates of a few hundred mrem per hour can produce count rates sufficient to cause problems with many detector systems.

In many cases, a spectrometer would have to measure neutrons with energies from thermal to 20 MeV to provide adequate dosimetric data. Measuring nine orders of magnitude is a major challenge. Fortunately, only part of the spectrum may need to be measured. For example, it may be reasonable to omit the low or high energy extremes of the spectrum if they include less than 5% of the total dose equivalent. Such a dosimetric limitation would permit using a low energy limit of 50 keV for about 90% of the spectra described by Ing and Makra.^{9,10} Many spectra from shielded fission sources could be measured using an upper limit of 6 MeV.

Resolution is the ability of a spectrometer to separate data that occur at adjacent energies. How much resolution a spectrometer must have is determined by the application. For example, measurements of shielding characteristics require good resolution in order to show the effects of the cross sections. Dosimetric related measurements may need good resolution only where the dose equivalent per neutron is changing rapidly as a function of neutron energy. Using this criterion, only 24 energy intervals would be required between 10 keV and 20 MeV. This represents an average resolution of 0.2 (full width at half maximum divided by the peak position).¹⁰ Normally, the best resolution obtainable from a detector is used for all measurements.

For radiation protection applications, a neutron spectrometer must be capable of making measurements outside of the laboratory. This implies a

compact, light weight system with low power consumption. Only small computers are suitable for data reduction in the field, so this requirement dictates which data reduction technique will be used. Field use also requires that the unit have easy setup, calibration, operation, and data reduction. Naturally, these characteristics would also simplify measurements in the laboratory.

The research and development effort to develop neutron spectrometers in the Hazards Control Department of LLNL was first reported in a progress report in 1972.¹¹ Subsequent developments have been reported on an irregular basis in later progress reports (all of which have numbers beginning with UCRL-50007). A more comprehensive report was made in 1978 on the system as it had evolved by then.¹² At that time, the system consisted of a combination of a liquid, or solid, organic scintillator for neutrons of MeV energies, and hydrogen, methane, or helium-3 filled proportional counters for lower energies. After 1978, the work became oriented toward improvements in the liquid scintillator system. These efforts have been discussed in progress reports and in a review paper in a special volume of the journal Radiation Protection Dosimetry that was devoted entirely to neutron dosimetry.¹³ We have concluded that, for the energy range from 1 to 20 MeV, a liquid scintillator is the best neutron spectrometer for radiation protection purposes. A multisphere system is used to measure lower energy neutrons.¹⁴ Even with its limited resolution, the multisphere system has proven more useful than the proportional counters reported in 1978.

2. DETECTOR

INTRODUCTION

Almost every possible interaction of neutrons with matter has been used to make spectrum measurements.¹⁵ As an introduction to a detailed discussion of the method that we have chosen for measuring fast neutrons, we will review some of the techniques previously used in this program.

Starting with Chadwick, elastic scattering has been widely used for detecting neutrons by the recoil ions produced. For example, a recoil-proton telescope uses an hydrogenous material as a proton radiator and a detector, separated at some distance, to measure the energy of the recoil protons. The low sensitivity and inherent directional response of a telescope limits its

usefulness for most radiation protection measurements; however, a telescope is well suited for measuring the spectra produced by standard sources, provided sufficient intensity or time are available, because "first principles" can be used to deduce the neutron spectrum from the recorded data. Johnson has provided a good review of proton-recoil telescopes.¹⁶

Neutrons are also often measured using the recoil ions they produce in gas-filled counters. In 1938, Baldinger et al. reported a technique for obtaining the neutron spectrum for the pulse-height spectrum produced by these recoil ions.¹⁷ Developments in gas recoil counters up to 1960 were reviewed by Ferguson.¹⁸ Recent use of proportional counters as neutron spectrometers, usually at energies below 1 MeV, has been reported by Benjamin et al., Kennett, and Ing et al.¹⁹⁻²¹

A hydrogen-filled proportional counter used as a neutron spectrometer can have good resolution and is capable of measuring neutrons with energies down to several keV. At higher energies (>1 to 2 MeV), it is not practical to make the counter large enough to guarantee that the majority of the recoil protons will lose all of their energy in the sensitive volume. Using a hydrocarbon gas (such as methane) or a mixture of a heavier gas (such as krypton) and hydrogen raises the upper energy limit by decreasing the range of the recoil protons, but neutron interactions with the carbon or the heavy gas add complications.

Some work, including that of Baldinger et al., has been done with counters filled with a heavier gas such as helium.²² Higher energies can be measured, because in a heavier gas the neutron imparts less energy to the recoil ion, and the ion has a greater stopping power. A disadvantage is the complexity of the collision cross sections for heavier gases compared with the monotonically decreasing and isotropic cross section of hydrogen.

Neutrons with energies in the range of 100 keV to 2 MeV can be measured with a proportional counter or ion chamber filled with helium-3 by using the n,p reaction.²³ The low energy limit is set by the resolution and the response to gamma rays. Helium recoils and a rapidly decreasing cross section become problems at high energies, although it is possible to discriminate against the recoils (and gamma rays) to some extent by using pulse-risetime techniques.²⁴ Such counters have been used successfully to measure spectra outside the biological shielding of power reactors where the majority of the neutrons have energies below 2 MeV.²⁵

Our earlier evaluations of hydrogen, methane, and helium-3 proportional counters were reported by Slaughter et al.¹² More recently, we investigated both hydrogen-xenon filled counters and a modified Benjamin-type counter. This work was not as successful as originally hoped, so these counters are no longer routinely used.

The ${}^6\text{Li}(n,\alpha)$ reaction has found several applications in fast neutron spectrometry. Considerable information has been published on spectrometers that use a thin foil of some lithium salt, usually lithium fluoride, mounted between two semiconductor charged-particle detectors.²⁶ These "sandwich" spectrometers function by measuring the alpha in one diode and the triton in the other. A coincidence requirement decreases the sensitivity to gamma rays and to the charged particles that the neutrons produce in the diodes. The charged particles become a significant background at higher energies, but this problem can be corrected to some extent by running a second set of diodes with no foil, or with a ${}^7\text{Li}$ fluoride foil, between them. The high interaction energy of the reaction, 4.78 MeV, and the resolution of the diodes limit the practical low energy response to about 0.5 MeV. Other configurations of the foil and detectors are possible that allow measurements to lower energies.²⁷ The sensitivity of all of these spectrometers is low, primarily because the radiator foils must be thin enough to prevent a significant decrease in the energy of the alphas as they leave the foil. A similar spectrometer can be made with the space between the diodes filled with ${}^3\text{He}$.²⁸

Neutrons can also be measured using the ${}^6\text{Li}(n,\alpha)$ reaction in a LiI scintillator. Fast neutron spectra can be measured if the scintillator is cooled to liquid nitrogen temperatures.²⁹ These detectors can be quite sensitive but require complicated apparatus to cool the crystal without also cooling the photomultiplier tube. Competing nuclear reactions can cause significant backgrounds.³⁰ Despite these problems, this type of spectrometer has found some use.³¹ One available to our program has, however, received little use.

Lithium iodide scintillators have received widespread use as detectors for the thermal neutrons produced inside polyethylene neutron moderators by fast neutrons. This is the basis of the multisphere spectrometer first described by Bramblett et al.¹⁴ It has sufficient sensitivity for most radiation protection measurements, it is reasonably easy to use, and it is

capable of covering the energy range from thermal to 10 MeV. Compared with the other techniques that have been discussed, this spectrometer has poor resolution; nevertheless, we have made considerable use of this type of spectrometer.

Our system uses a 13-mm-diameter by 13-mm-high LiF crystal. Measurements are made with the detector bare and with it enclosed in a cadmium shield or in polyethylene spheres that are 51, 76, 127, 203, or 305 mm in diameter. The weights of the larger spheres are a disadvantage, but the biggest problem with this system is selecting the proper technique for deducing the neutron spectrum over such a wide energy range from the limited amount of input data. The program we used previously, LOUHI, requires a large computer.³² Recently we have written a program called MINKY that will run on a small computer. Both of these programs allow previously obtained information, such as the results from the liquid scintillator, to be used as part of the input data.

The first scintillation detectors to receive wide use were organic crystals such as anthracene or stilbene. These were soon put to use for neutron spectrometry.³³ The entire distribution of recoil protons is deposited in the scintillator, and techniques similar to those of Baldinger et al. must be used to obtain the neutron spectrum from the data.¹⁷ Edge effects are reduced because the proton ranges are shorter than in a gas-filled counter. Organic scintillators do, however, have a number of problems, the greatest being the nonlinear relationship between the light output and the proton energy deposited. Common organic crystals cannot be grown very large because the planar characteristics of the molecules result in striations that prevent efficient light transmission. Moreover, the light produced depends upon the orientation of the proton track relative to the crystal lattice.³⁴ Despite these problems, we used a stilbene crystal in earlier work, largely because of the success of Broek and Anderson with such a detector.³⁵

LIQUID SCINTILLATORS

The problems caused by the limited size and anisotropic response of an organic crystal can be overcome by using plastic or liquid organic scintillators. Plastic scintillators can be cast in almost any shape, while the cell determines the shape of a liquid scintillator. Each of the many

liquid scintillators available has its performance optimized for a particular application. We use the one most widely used for fast neutron spectrometry which has naphthalene, activators, and a wave shifter dissolved in highly purified para-xylene. To work properly, the scintillator must be thoroughly deoxygenated, which can be done by sparging with dry nitrogen. Although it is now available from several sources, this scintillator was previously supplied almost exclusively by Nuclear Enterprises Ltd. of Edinburgh, Scotland, as NE 213. We will use this identification because all of our detectors were obtained from the now defunct U. S. subsidiary of Nuclear Enterprises, and many publications deal with this scintillator. A similar scintillator is now manufactured as BC 501 by the Bicron Corporation, Newbury, Ohio.

The NE 213, which is primarily carbon and hydrogen with 1.213 hydrogen atoms per carbon atom, has a density of 0.874 grams per cubic centimeter, resulting in 0.0398 carbon and 0.0433 hydrogen atoms per barn-cm. The light output is 78% that of anthracene. (Anthracene is the standard normally used for organic scintillators. On this scale, NaI has a light output of 230%.) The index of refraction is 1.508, which matches common types of glass fairly well. The scintillator is reasonably transparent to its own emissions. The maximum emission occurs at 425 nanometers, which is compatible with common photomultiplier tubes. Because xylene is flammable, handling problems must be considered. Xylene also has a large coefficient of thermal expansion, so the cells used to hold the scintillator must be designed accordingly. The positions in which some cells can be operated must be limited to prevent the nitrogen bubble used to accommodate the expansion from interfering with light collection.

SCINTILLATORS IN USE AT LLNL

The Social Projects Division of the Hazards Control Department of Lawrence Livermore National Laboratory has seven NE 213 detectors in a variety of shapes and sizes. This allows us to select the optimum detector for each measurement. The size most often referred to in the literature is a right cylinder that is 51 mm in diameter by 51 mm high. We have three of these, each of which has unique characteristics that make it suitable for different situations. Two other detectors, one 13 mm by 13 mm and the other 25 mm by 25 mm, are useful in more intense radiation fields. The remaining two detectors are not symmetric; one is 114 mm in diameter by 51 mm high, and the other is 38 mm in diameter by 76 mm high. All of the detectors are shown in Fig. 1.

Figure 1. NE 213 detectors used by the Special Products Division of the Hazards Control Department of LLNL, with the most recently assembled unit shown out of its housing.

One of the newer 51-mm by 51-mm units is shown out of its housing so the components can be seen.

The oldest 51-mm by 51-mm detector (obtained in 1976) has the scintillator cell, photomultiplier tube, and magnetic shield assembled as an integral unit. This cell can operate in any position because it uses a capillary tube wound around the outside of the cell as the expansion chamber. Some cells with this design have a light reflector in direct contact with the scintillator solution. This causes problems because deoxygenating the large surface area of the reflector is difficult. Both the height and length of the scintillator pulses are decreased by oxygen contamination, although this detector has not exhibited this problem.

The photomultiplier tube (PMT) used with this detector, an RCA-8575 (RCA, Lancaster, PA), has a 46-mm-diameter, bi-alkali photocathode that has good efficiency for producing photoelectrons and a sensitivity compatible with the blue light produced by the scintillator. A focused dynode structure and a 50-ohm anode impedance accommodate fast pulses. This PMT also has acceptable dark current, noise, and after pulsing. External shields in contact with the glass envelope must be operated at cathode potential to prevent noise or damage to the tube. This can cause safety problems since the tube must be enclosed in a magnetic shield, and the cathode must operate at a negative high voltage in order to operate the anode at ground potential as required for fast timing.

The 25-mm by 25-mm detector was also purchased as an integral unit with a cell that can be operated in any position. This detector has also not shown any serious degradation in its output pulses. It uses an 8575 PMT because smaller diameter tubes with suitable characteristics were not available in 1975 when this unit was assembled. A smaller cell is useful when the intensity of the source would produce an excessive count rate in a larger detector. There is also a lower probability that a neutron will undergo multiple scattering in the detector, but this is coupled with an increased chance that the recoil proton may escape the cell without depositing all of its energy.

Much more intense sources can be measured with the 13-mm by 13-mm detector and with less multiple scattering but with more edge effect problems. This detector was assembled locally using an 8575 for the same

reasons that this PMT was used on the detectors already described. The cell has a simple expansion chamber that is mounted opposite the PMT, so this detector must always be operated pointing up and irradiated from the side.

The 38-mm-diameter by 76-mm-long detector was also assembled here using an 8575 PMT. This geometry was chosen for two reasons: 1) to provide a smaller area for the neutrons to intercept, in order to decrease sensitivity, and 2) to provide a long path length to increase the probability of interaction at higher energies. Unfortunately, the longer path length also increases multiple scattering, and the smaller diameter increases edge effects. The scintillator has a gas bubble within the cell to accommodate expansion; therefore, this cell cannot be operated pointing down, as that would put the bubble between the PMT and the scintillator.

Another detector without a separate expansion chamber is the 114-mm-diameter by 51-mm-long unit. This detector was obtained as an integral unit using an RCA-4525 PMT that has a bi-alkali photocathode and Venetian-blind dynodes. Such a dynode configuration limits the speed of the pulse response. This cell geometry offers increased sensitivity with reasonable edge effects but with increased multiple scattering.

We also have two newer 51-mm-by 51-mm detectors that were assembled here. These detectors incorporated features that are the result of studies we made. They differ from one another only in how the cells are mounted, which determines the orientations in which they can be operated. The diagram in Fig. 2 gives details of their construction. The cell has the expansion chamber attached to its side in such a way that it can be operated in any position that keeps the chamber pointing up. Normally, this allows horizontal or vertical operation with the PMT below the cell, as shown in Fig. 2. This geometry was defined as horizontal/up. We purchased one of the cells with both ends unpainted and then applied light-reflecting paint to the opposite end of the cell from that normally covered. This cell can be operated horizontally or vertically with the PMT above the cell. This is the unit shown out of its housing in Fig. 1. We defined this geometry as horizontal/down.

An important feature of these detectors is a 25-mm-long, 51-mm-diameter glass light pipe placed between the cell and the PMT. A transparent silicone rubber potting compound is used to join the cell to the light pipe and the light pipe to the PMT. The detectors use an RCA-8850 PMT, which is similar to

Figure 2. Diagram of modified NE 213 detectors built at LLNL using components based on experimental results.

the 8575 except that the first dynode is covered with a semiconductor secondary-electron emitter. This emitter provides larger secondary electron yields than the CuBe dynode used in the 8575. Increasing the secondary electron yield of the first dynode improves the resolution of the PMT for single photoelectrons. Our experience indicates that the special features of this PMT have little effect on the quality of the data obtained; therefore, the added cost is probably not justified for this application.

It is difficult to locate the center of the scintillator cell within the large housings needed to enclose these detectors. We have marked the housing on the front to denote the axis of the cell; we marked it on the side to denote the half height of the cell. The locations of these marks were based on the dimensions of the cell and the known geometry of the assembly. To test the adequacy of this procedure, we made measurements with a collimated gamma source. The center of the cell deduced from these measurements was within a millimeter of the markings.

DETECTOR EFFICIENCY

The size of the scintillator determines the probability that an incident neutron will produce a recoil proton in the detector. Efficiency is normally defined in terms of the probability for the first collision between a neutron and a proton. This depends both on the distance traversed by the neutron in the counter and on the chance that the neutron will interact with any of the elements in the detector. The probabilities depend on the cross sections, and the track lengths depend upon the geometry of the detector and the orientation of the detector to the neutron beam. In order to calculate efficiency, assumptions must be made about the direction of incidence of the neutrons. We assume a plane beam incident on the flat end of a cylindrical detector. This geometry, or a good approximation to it, occurs in many cases; however, neutron fields may be more isotropic, and it is not uncommon to irradiate the cylindrical side of a detector.

Assuming the detector consists only of hydrogen and carbon, the fraction of the first interactions that occurs between the neutron and hydrogen is

given by the ratio

$$\frac{n_H \sigma_H}{n_H \sigma_H + n_C \sigma_C},$$

where

n_H = the density of hydrogen atoms,
 n_C = the density of carbon atoms,
 σ_H and σ_C = the total cross sections.

If the detector is not thin, a term must be included to account for neutrons lost from the beam as they traverse the detector. If x is the detector thickness, this term is given by

$$1 - e^{-x(n_H \sigma_H + n_C \sigma_C)}.$$

The product of these two terms as a function of neutron energy and detector thickness is shown in Fig. 3. For the thicker detectors, the effects of the resonances in the carbon cross sections are clearly shown. This illustrates the necessity for correcting for the self-attenuation of thick detectors. These curves also illustrate the importance of using accurate carbon cross sections for thicker detectors.

LIGHT OUTPUT OF NE 213

A knowledge of how the light output of the scintillator varies as a function of gamma-ray (electron) energy, neutron (proton) energy, and time is vital to reducing data obtained with an organic scintillator from neutrons. Gamma-ray sources are commonly used to provide pulse-height calibrations. The light output as a function of proton energy is nonlinear and thus produces a distortion in the recorded data that cannot be corrected unless the function is known. The temporal response is important for pulse-shape discrimination, a property that allows proton- and electron-produced pulses to be separated electronically.

A quick survey of the literature produced a dozen papers that gave the light output of NE 213, but there was considerable disagreement in the data. Two data sets that do compare reasonably well are those of Verbinski et al.

Figure 3. Efficiency of NE 213 detectors as a function of neutron energy and detector thickness.

and Benjamin.^{36,37} The variations in the published values indicated that light output might be detector specific and that we would have to make our own measurements using several of our detectors. These detectors will be identified as A, B, and C in the following text, tables, and figures. To test the effects of aging, we measured the light output from both the new horizontal/up 51-mm by 51-mm detector (A) and the older integral 51-mm by 51-mm detector (B). We included the integral 25-mm by 25-mm detector (C) to study the effect of detector size.

Light Output as a Function of Electron Energy

Gamma rays are routinely used for pulse-height calibrations of measurements made with the NE 213, and the neutron light output is often given in terms of the electron energy that produces the same amount of light. Thus, our first experiment measured the light produced in the NE 213 by electrons at a number of energies.

Due to the low atomic number of the constituents of the NE 213, the predominant gamma-ray interaction above 100 keV is the Compton effect. In this case, variations in the resolution of the detector make it difficult to assign energy values to the features of the continuous pulse-height distribution obtained. For energies below 100 keV, total energy peaks are obtained both because the photoelectric cross section is sufficiently large and because multiple scattering can result in total energy absorption. In this case, peaks are obtained that can be correlated to the energy of the incident gamma ray. We measured peaks produced by ¹⁰⁹Cd, ²⁴¹Am, and ⁵⁷Co.

Data on light produced in a detector for known electron energies can be obtained from a Compton scattering experiment.^{38,39} Figure 4 is a diagram of the physical arrangement of our scattering experiment. Gamma rays from ⁵⁷Co, ²²Na, ²⁰⁷Pb, or ¹³⁷Cs were backscattered from the detector under study to a second detector. The light produced by recoil electrons in the first detector was measured whenever the signals from the two detectors occurred in coincidence. A 100-mm-thick lead shield was placed between the source and the second detector to decrease chance coincidences.

The geometry used was chosen because the source irradiated the entire volume of the detector, as normally occurs during calibrations. An improperly designed detector can have significant variations in pulse-height response

Figure 4. Diagram of the configuration of the Compton-scattering experiment.

throughout its volume; therefore, a calibration made with a collimated beam might apply only to the irradiated portion of the detector. Some of our preliminary measurements suffered from this problem. A scattering angle of exactly 180 degrees was not used, because a source that has gamma rays emitted in a cascade is as apt to produce coincidence detector signals as a backscattered photon in coincidence with a scattered electron. Annihilation photons, like those produced by ^{22}Na , are always 180 degrees apart and would always cause a coincidence.

The source-to-detector and detector-to-detector distances must be large enough that the solid angle subtended by the detectors does not cause a significant broadening in the pulse-height spectrum of the recoil electrons. Monte Carlo techniques were used to make an integration over the detector volumes to choose the distances for this experiment. A spacing of 250 mm between the centers of the detectors produced geometrical broadening of the electron-energy distribution that was consistent with the resolution of the detectors. The distance of 160 mm between the source and the detector for the recoil photons was determined by the space needed to get the 100 mm of lead between them. This geometry resulted in a photon scattering angle of 147.4 degrees. The Monte Carlo calculations showed that the centroids of the measured distributions would be essentially the same as those obtained from a point source and point detectors, despite the broadening in the distributions caused by the size of the detectors. The calculations also showed that the distributions became more symmetric as the scattering angle increased. Each of the three detectors was used, in turn, to detect the recoil electrons, but the recoil photons were always detected using one of the 51-mm by 51-mm detectors.

A block diagram of the electronic components used is given in Fig. 5. Anode signals from the detectors went to two ORTEC model 583 constant-fraction differential discriminators (ORTEC, Oak Ridge, TN). To decrease chance coincidences, the discriminator used with the recoil photon detector was set to operate only for signals produced by photons with energies below 250 keV, which is the maximum energy that the scattered photons could have for this geometry. The outputs of the discriminators operated a coincidence circuit that had a 10-ns resolving time. This short resolving time further reduced the probability of chance coincidences. Annihilation photons from a ^{22}Na source were used to establish the operating parameters for the coincidence system.

Figure 5. Block diagram of the electronic components used for the Compton-scattering experiment.

A coincidence produced a signal that opened the input gate of a Nuclear Data ND-620 multichannel analyzer (MCA) (Nuclear Data, Schaumburg, IL). The pulse-height signals recorded by the MCA were obtained from the tenth dynode of the PMT on the recoil-electron detector. These signals were amplified with a charge-sensitive preamplifier and a Tennelec TC-202BLR linear amplifier (Tennelec, Oak Ridge, TN). Each of the detectors had a separate high voltage supply, preamplifier, and linear amplifier to reduce the need for changes in the settings as the detectors were used at the different positions of the experiment.

When these detectors are used for neutron spectrometry, two gain settings to measure the entire energy range of interest are needed. The two settings are obtained by changing both the high voltage and the linear amplifier gain. Gamma-ray light output data were obtained at the two high voltage settings normally used for neutron measurements, but with no change in the amplifier gain. The total energy peaks from ^{109}Cd , ^{241}Am , and ^{57}Co were recorded at both gains. At the lower high voltage setting ($\sim -1700\text{V}$), Compton scattering data were obtained using ^{22}Na , ^{207}Bi , and ^{137}Cs . At the higher voltage (-2000 V), ^{57}Co also produced anode signals large enough for scattering measurements. The responses for the 1.27 MeV gamma rays from ^{22}Na and the responses for the 1.06 and 1.77 MeV gamma rays from ^{207}Bi were not linear at -2000 V , so these data were not used.

A continuum, approximated by a straight line, was subtracted from the data. Then a centroid was calculated to locate the peak. The limited resolution of the detectors made it necessary to use weighted averages of energies for the photons emitted by ^{109}Cd and ^{57}Co which each have multiple emissions at closely spaced energies. The gamma-ray and electron energies used are given in Table 1.

The length of the measurements were controlled by the intensity of the available sources which were mostly quite small. It required 90 hours to get sufficient data from the ^{207}Bi source but only three hours for the ^{109}Cd source. Less time was required for the low energy sources, because they did not require coincidence measurements. They did, however, have background contributions that had to be measured and subtracted from the data. Data, taken in multiple one- to ten-hour intervals, were compared to see if any significant drifts had occurred. Segments for which the drifts were acceptable were summed into a single data set. Normally all of the data could be used.

Table 1. Gamma-ray and Compton recoil electron energies used.

Source	Photon energies (MeV)	Energy of Compton electrons (MeV)
^{109}Cd	0.02261	----
	0.08804	----
^{241}Am	0.05954	----
^{57}Co	0.12372	0.03816
^{22}Na	0.51100	0.33122
	1.27455	1.04674
^{207}Bi	0.56965	0.38311
	1.06363	0.84363
	1.77022	1.53042
^{137}Cs	0.66166	0.46622

A pulse-height calibration was made with a pulser before and after each run to monitor long-term drifts in both amplifier gain and analyzer stability. The pulser data also provided an arbitrary voltage scale for the pulse-height calibration. To put the gamma-ray data on a voltage scale, we had to assume that differences in the pre- and post-run calibrations represented a linear drift between those times. Only small variations were encountered.

The uncertainties in the centroid calculations for the gamma-ray data and the uncertainties from a linear fit to the pulser data were combined to provide a total uncertainty for the centroid values. A weighted average of the data was made for each combination of source, detector, and high voltage. The results for the data taken in the linear region of detector performance are given in Table 2.

An arbitrary normalization to one light unit at an energy of 341 keV was chosen because this is the energy of the Compton edge for the annihilation photons from ^{22}Na . We use this point for both low and high gain calibrations. One of our light units is equivalent to 0.2668 of the units used by Verbinski et al.³⁶ Agreement between the detectors was better than expected. The data for detector A (the new 51-mm by 51-mm detector), at

Table 2. Light output as a function of electron energy. One light unit occurs at 0.341 MeV.

Electron energy (MeV)	Low High Voltage		
	Detector A	Detector B	Detector C
0.124	0.347 ± 0.003	0.350 ± 0.002	0.347 ± 0.004
0.331	0.961 ± 0.014	0.955 ± 0.002	0.949 ± 0.005
0.383	1.126 ± 0.006	1.149 ± 0.004	1.147 ± 0.026
0.466	1.394 ± 0.005	1.415 ± 0.005	1.428 ± 0.013
0.844	2.539 ± 0.014	2.610 ± 0.009	2.621 ± 0.027
1.047	3.107 ± 0.005	3.147 ± 0.009	3.138 ± 0.021
1.530	4.626 ± 0.036	4.662 ± 0.040	4.421 ± 0.094
Electron energy (MeV)	High High Voltage		
	Detector A	Detector B	Detector C
0.0226	0.0559 ± 0.0006	0.05458 ± 0.00005	0.0550 ± 0.0002
0.0382	0.0982 ± 0.0015	0.0971 ± 0.0008	0.0984 ± 0.0015
0.0595	0.1573 ± 0.0004	0.1583 ± 0.0009	0.160 ± 0.003
0.0880	0.234 ± 0.007	0.228 ± 0.007	0.241 ± 0.015
0.124	0.349 ± 0.002	0.352 ± 0.001	0.349 ± 0.007
0.331	0.959 ± 0.003	0.953 ± 0.002	0.954 ± 0.013
0.383	1.134 ± 0.009	1.152 ± 0.005	1.161 ± 0.011
0.466	1.405 ± 0.004	1.394 ± 0.005	1.364 ± 0.013

energies up to 500 keV, are plotted on a log-log scale in Fig. 6.

Uncertainties in the data are of the same order of magnitude as the size of the symbols. At these energies, the light is best fit by a power function with a multiplicative constant of 3.133 and energy raised to a power of 1.060 ($L = 3.133E^{1.060}$). Similar data for energies above 100 keV are plotted in Fig. 7. These data are linear with a non-zero intercept that is caused by the non-linearity of the response at low energies. A weighted, least-squares fit to these data gives $L = -0.021 + 2.998E$. This light intercept is equivalent to an energy intercept of 7 keV.

The multiparameter capabilities of the ND-620 MCA enabled us to record the complete Compton recoil-electron spectrum from the scattering detector at the same time we measured the recoil electrons at a specific energy. We extracted peaks and half heights from these data and reduced them to light values using the same techniques used for the scattering data. These values, converted to electron energies using the fits to the scattering data, are listed as a function of the energy of the forward scattered Compton electrons in Table 3. The agreement between the values from the high and low high voltage settings indicates that no significant change in resolution occurs with changes in high voltage. Differences between detectors are not large, but they are significant and reflect the poorer resolution of the older detectors.

These data can be used to assign energy values to easily measured parameters of the Compton distribution such as the peak or the half height of the edge. From these results, it is clear that assigning the energy of the maximum recoil electron (Compton edge) to the half height is not a good procedure. Dietze has derived a more sophisticated procedure based upon Monte Carlo calculations.⁴⁰ His data may be parameterized to obtain an approximate relation between the Compton edge location and the peak and half height values. Similar data, derived from our measurements, are compared with the Dietze results in Fig. 8. The differential aspects of this approach give large uncertainties in the values obtained from the experimental data. Our results don't agree with those of Dietze. Other commonly used techniques that place the Compton edge at a fixed fraction of the half height or at some multiple of the peak also do not give results consistent with our measurements.

It isn't necessary to know the location of the Compton edge if a calibration, made under normal experimental conditions, is available that

Figure 6. Light output of NE 213 as a function of electron energy for energies below 1 MeV. The line is the power function $L = 3.133 E^{1.060}$.

Figure 7. Light output of NE 213 as a function of electron energy for energies above 120 keV. The line is the function $L = -0.021 + 2.998 E$.

Table 3. Equivalent energy for locations of peaks and half heights of Compton electron distributions.

Compton electron energy	Detector	High voltage	Peak MeV	Half height MeV
0.34067 (²² Na)	A	Low	0.302 ± 0.001	0.356 ± 0.001
	A	High	0.302 ± 0.013	0.359 ± 0.001
	B	Low	0.299 ± 0.002	0.356 ± 0.001
	B	High	0.293 ± 0.010	0.357 ± 0.001
	C	Low	0.293 ± 0.001	0.354 ± 0.002
	C	High	0.290 ± 0.003	0.350 ± 0.003
0.39326 (²⁰⁷ Pb)	A	Low	0.359 ± 0.005	0.419 ± 0.001
	A	High	0.363 ± 0.010	0.418 ± 0.010
	B	Low	0.359 ± 0.009	0.425 ± 0.005
	B	High	0.361 ± 0.001	0.427 ± 0.001
	C	Low	0.354 ± 0.001	0.426 ± 0.001
	C	High	0.351 ± 0.001	0.421 ± 0.001
0.47734 (¹³⁷ Cs)	A	Low	0.446 ± 0.001	0.509 ± 0.001
	A	High	0.447 ± 0.003	0.508 ± 0.001
	B	Low	0.444 ± 0.002	0.516 ± 0.001
	B	High	0.445 ± 0.002	0.516 ± 0.001
	C	Low	0.437 ± 0.001	0.517 ± 0.001
	C	High	0.414 ± 0.002	0.491 ± 0.002
0.85762 (²⁰⁷ Pb)	A	Low	0.818 ± 0.005	0.908 ± 0.003
	B	Low	0.814 ± 0.011	0.922 ± 0.007
	C	Low	0.803 ± 0.005	0.930 ± 0.003
1.0671 (²² Na)	A	Low	0.996 ± 0.002	1.100 ± 0.002
	B	Low	0.986 ± 0.002	1.112 ± 0.002
	C	Low	0.959 ± 0.004	1.096 ± 0.003
1.54694 (²⁰⁷ Pb)	A	Low	1.503 ± 0.014	1.616 ± 0.006
	B	Low	1.478 ± 0.025	1.642 ± 0.011
	C	Low	1.427 ± 0.021	1.671 ± 0.013

Figure 8. The ratio of the energy of the peak to the energy of the Compton edge as a function of a parameter derived from the peak and half height of the Compton distribution.

gives energy or light values for the peaks or half heights. For our pulse-height calibrations, we use the light values we measured for the half heights of the Compton edges because the half height can usually be found with good precision, even with simple techniques. We use the half heights of ^{207}Bi and ^{22}Na for low-gain measurements; we use the half height from ^{137}Cs , the half height from the annihilation gamma rays of ^{22}Na , and the peak from ^{241}Am at high gains. We also use the half height of the Compton distribution produced by the 4.43 MeV carbon de-excitation gamma rays from a beryllium (α, n) source for calibrating low gain measurements. This gamma ray and the 6.14 MeV oxygen de-excitation gamma ray from a carbon (α, n) source produce a small double escape peak from pair production that falls on top of the Compton distribution. This peak is well suited for calibration because it is easy to find and because it is associated with a specific electron energy. The half height of the Compton edge produced by the carbon de-excitation gamma rays occurs at 12.88 light units. The double escape peak from these gamma rays occurs at 10.22 light units and from the oxygen de-excitation gamma rays, at 15.29 light units. Using calibration points with large light values significantly decreases the amount of extrapolation required for the pulse-height calibrations of measurements made with an upper neutron energy of 20 MeV.

Light Output as a Function of Proton Energy

Three experiments were performed to determine the light output of the NE 213 as a function of neutron energy. Detectors A, B, and C were used in the first experiment, A and B in the second experiment, and only A in the third experiment.

Using Monoenergetic Neutrons

In the first experiment, all three detectors were irradiated at the LLNL Cyclograff Facility with monoenergetic neutrons produced by $\text{Li}(p,n)$ and $\text{D}(d,n)$ reactions. The lithium target was $201 \mu\text{g}/\text{cm}^2$ of LiF deposited on a tantalum backing, and the deuterium target was $4.64 \text{ mg}/\text{cm}^2$ of erbium deuteride on a tantalum backing. Three proton energies (2.2, 2.7, and 3.7 MeV) and two deuteron energies (2.3 and 7.0 MeV) were used. A variety of beam-line-to-detector angles were used for each ion energy to produce 19 neutron energies spaced approximately logarithmically from 190 keV to

9.8 MeV. The detectors were always placed 1 m from the target, with the angles and distances set using a specially constructed protractor. A second group of lower energy neutrons was produced from the Li target by the 2.7- and 3.7-MeV protons. Data from these neutrons were not included in the light output results but were used to test both the reproducibility and the data reduction programs.

Runs lasted up to an hour, because low beam currents were used to prevent damage to the targets. Even running three detectors simultaneously, only a few of the points could be repeated because of the limited accelerator time available and concurrent use for other experiments. Excellent agreement was obtained for the few cases that were repeated. Some of the data for 3.7-MeV protons on the Li target were measured at both low and high gain. No pulse-shape discrimination was used for these measurements, so the data included the response of the detectors to the 6.14-MeV gamma rays produced by the $^{19}\text{F}(p,\alpha\gamma)$ reaction. This was particularly noticeable at low gain. These data subsequently exposed a problem in detector linearity.

Calculations of neutron energy were made from the incident ion energy and the angle to the detector. The effect of the energy loss of the incident ions in the target was evaluated by summing over many interactions at random depths. Similarly, the energy spread due to the solid angles subtended by the detectors was included by summing over randomly chosen interaction points within the detectors. The results of these calculations were used to assign uncertainties to the energy values.

We later returned to the Cyclograff to run 2.1-MeV protons on the lithium target and 2.2-, 4.0-, 6.5-, and 8.0-MeV protons and 2.6-MeV deuterons on a 3.1-mg/cm² erbium-tritide target. The 25-mm by 25-mm detector (Detector C) was not included in these runs because we knew its response would be poor to the higher energy neutrons that would be obtained. For these runs, three beam-line-to-detector angles were used for each combination of ion and energy, so a total of 18 neutron energies, from 160 keV to 18.7 MeV, were obtained. Some of the energies allowed direct comparisons with data obtained during the first experiment.

Monoenergetic neutrons produce protons in the detector with all energies up to the energy of the neutrons. This energy distribution is distorted by the nonlinear light output and the limited resolution of the detector. Corrections must be made in order to relate the measured light output to

neutron energy. Baldinger, Huber, and Staub showed that, for a linear relationship between energy and pulse-height, the neutron energy should be assigned to the peak that results from taking the slope of the pulse-height distribution.¹⁷ We assigned the neutron energies to the peaks obtained in a first derivative of the data.

It was necessary to use an iterative procedure to evaluate the data because a mathematically correct derivative requires the same knowledge about the light output that we were trying to determine. For the data from the first Cyclograff run, the first iteration used a Gaussian-weighted, multi-point derivative. We fit a fifth degree logarithmic polynomial,

$$\log(L) = \sum_{i=0}^5 A_i [\log(E)]^i,$$

to these data. With this fit, the next iteration could take the nonlinear light output into consideration. The equation used for the nonlinear derivative was that given by Benjamin.³⁷ A numerical approximation must be used to obtain the derivative. We chose simple differences between adjacent channels. Differentiation was followed, when necessary, by one or more applications of five-channel, Gaussian-weighted smoothing. The centroid of the peak was found, and the resulting light value was assigned to the neutron energy that produced the data. These data were fit with the logarithmic polynomial, and the entire process was repeated until centroid values no longer varied between runs. Normally only a few iterations were required. The results from the first Cyclograff run were used as the starting point for the reduction of the data from the second run. Data from the second run did not produce a significant change in the polynomial fit obtained from the first run.

Pulse-height calibrations were made for these runs using ²⁴¹Am, ²²Na, and PuBe sources. Our measurements of light output as a function of gamma-ray energy allowed the neutron data to be expressed in terms of both the light produced and the electron energy that would produce that amount of light. These values are given in comparison to neutron energy in Table 4. The uncertainties given for the energies are the full width of the distribution caused by the combination of target thickness and detector solid angle. Both the light output and the equivalent electron energies show the combined uncertainties of the centroid calculations and the pulse-height calibrations.

Table 4. Light output and equivalent electron energy as a function of proton energy deduced from monoenergetic neutrons (page 1 of 2).

Proton energy (MeV)	Detector A		Detector B		Detector C	
	Light (L.U.)	Electron energy (MeV)	Light (L.U.)	Electron energy (MeV)	Light (L.U.)	Electron energy (MeV)
0.150 ± 0.007	0.0562 ± 0.0003	0.0226 ± 0.0001	0.0553 ± 0.0027	0.0229 ± 0.0010		
0.187 ± 0.005	0.0685 ± 0.0006	0.0272 ± 0.0002	0.0652 ± 0.0004	0.0266 ± 0.0002	0.0598 ± 0.0008	0.0244 ± 0.0003
0.240 ± 0.008	0.0853 ± 0.0003	0.0334 ± 0.0001	0.0732 ± 0.0020	0.0297 ± 0.0008		
0.249 ± 0.006	0.0887 ± 0.0008	0.0347 ± 0.0003	0.0847 ± 0.0008	0.0340 ± 0.0003	0.0843 ± 0.0016	0.0336 ± 0.0006
0.303 ± 0.007	0.1092 ± 0.0009	0.0422 ± 0.0003	0.1019 ± 0.0009	0.0404 ± 0.0003	0.103 ± 0.003	0.0406 ± 0.001
0.318 ± 0.008	0.114 ± 0.002	0.0440 ± 0.0007	0.100 ± 0.002	0.0397 ± 0.0007		
0.358 ± 0.007	0.133 ± 0.002	0.0508 ± 0.0007	0.125 ± 0.001	0.0489 ± 0.0007	0.131 ± 0.002	0.0508 ± 0.0007
0.439 ± 0.009	0.177 ± 0.002	0.0666 ± 0.0007	0.166 ± 0.002	0.0637 ± 0.0007	0.162 ± 0.003	0.0640 ± 0.0011
0.550 ± 0.011	0.259 ± 0.003	0.0953 ± 0.0010	0.245 ± 0.005	0.0917 ± 0.0017	0.244 ± 0.002	0.0918 ± 0.0007
0.599 ± 0.018	0.275 ± 0.003	0.101 ± 0.001	0.254 ± 0.003	0.0948 ± 0.0010		
0.633 ± 0.010	0.340 ± 0.008	0.123 ± 0.003	0.328 ± 0.007	0.120 ± 0.002	0.324 ± 0.011	0.119 ± 0.004
0.844 ± 0.012	0.501 ± 0.006	0.176 ± 0.002	0.462 ± 0.012	0.166 ± 0.004	0.453 ± 0.005	0.162 ± 0.002
0.963 ± 0.025	0.597 ± 0.004	0.209 ± 0.001	0.556 ± 0.008	0.197 ± 0.003		
0.968 ± 0.015	0.619 ± 0.006	0.217 ± 0.002	0.574 ± 0.014	0.203 ± 0.005	0.568 ± 0.007	0.201 ± 0.004
1.279 ± 0.019	0.948 ± 0.038	0.324 ± 0.012	0.907 ± 0.022	0.311 ± 0.007	0.931 ± 0.011	0.319 ± 0.004
1.281 ± 0.029	0.898 ± 0.008	0.308 ± 0.003	0.848 ± 0.015	0.292 ± 0.005		
1.626 ± 0.018	1.35 ± 0.02	0.460 ± 0.007	1.30 ± 0.03	0.422 ± 0.010		
1.636 ± 0.024	1.14 ± 0.04	0.456 ± 0.014	1.28 ± 0.02	0.436 ± 0.007	1.27 ± 0.04	0.432 ± 0.014
1.984 ± 0.031	1.84 ± 0.04	0.626 ± 0.014	1.73 ± 0.05	0.588 ± 0.017	1.70 ± 0.04	0.578 ± 0.014
2.398 ± 0.023	2.44 ± 0.05	0.836 ± 0.017	2.34 ± 0.07	0.795 ± 0.024		
2.831 ± 0.021	3.06 ± 0.05	1.04 ± 0.02	2.97 ± 0.07	1.01 ± 0.02	2.90 ± 0.04	0.985 ± 0.115
3.039 ± 0.021	3.39 ± 0.06	1.15 ± 0.02	3.31 ± 0.07	1.12 ± 0.02		
3.044 ± 0.026	3.46 ± 0.07	1.18 ± 0.02	3.39 ± 0.13	1.15 ± 0.04		
3.483 ± 0.042	4.08 ± 0.09	1.39 ± 0.03	4.01 ± 0.11	1.36 ± 0.04	3.97 ± 0.09	1.37 ± 0.03

Table 4. Continued (page 2 of 2).

	Detector A			Detector B		Detector C	
	Proton energy (MeV)	Light (L.U.)	Electron energy (MeV)	Light (L.U.)	Electron energy (MeV)	Light (L.U.)	Electron energy (MeV)
3C	3.893 ± 0.031	4.92 ± 0.14	1.67 ± 0.05	4.78 ± 0.13	1.62 ± 0.04		
	4.371 ± 0.033	5.70 ± 0.12	1.94 ± 0.04	5.67 ± 0.14	1.92 ± 0.05		
	4.545 ± 0.072	5.97 ± 0.15	2.03 ± 0.05	5.82 ± 0.21	1.98 ± 0.07	5.78 ± 0.11	1.96 ± 0.04
	5.284 ± 0.094	7.05 ± 0.12	2.39 ± 0.04	7.07 ± 0.14	2.40 ± 0.05	7.26 ± 0.27	2.46 ± 0.09
	5.455 ± 0.046	7.62 ± 0.17	2.59 ± 0.06	7.59 ± 0.22	2.58 ± 0.07		
	5.551 ± 0.039	7.85 ± 0.17	2.67 ± 0.06	7.84 ± 0.26	2.66 ± 0.09		
	6.554 ± 0.059	9.57 ± 0.24	3.25 ± 0.08	9.31 ± 0.09	3.16 ± 0.03	9.51 ± 0.42	3.23 ± 0.14
	6.901 ± 0.058	10.4 ± 0.4	3.53 ± 0.14	10.3 ± 0.3	3.49 ± 0.10		
	7.862 ± 0.061	11.8 ± 0.3	4.01 ± 0.10	11.7 ± 0.3	3.97 ± 0.10	12.2 ± 0.4	4.14 ± 0.14
	9.801 ± 0.051	15.1 ± 0.5	5.13 ± 0.17	13.9 ± 0.1	4.71 ± 0.03	15.6 ± 0.3	5.29 ± 0.10
	15.676 ± 0.096	29.2 ± 0.9	9.92 ± 0.31	29.6 ± 1.2	10.0 ± 0.4		
	17.488 ± 0.097	33.2 ± 1.1	11.3 ± 0.4	33.3 ± 1.7	11.3 ± 0.6		
	18.736 ± 0.095	35.4 ± 1.1	12.0 ± 0.4	35.6 ± 1.6	12.1 ± 0.5		

As shown in Fig. 9, data from the three detectors are in good agreement, despite the age and geometry differences. To simplify the plot in Fig. 9, no uncertainties are shown. A plot of the data from Detector A is given in Fig. 10. The data points are shown as ellipses, the sizes of which represent the uncertainties. The dotted line is a fifth degree logarithmic fit to the data generated from the coefficients given in Table 5.

Using Neutron Scattering and Time-of Flight

Because we weren't sure that the iterative process compensated completely for the nonlinearity at low energies, we ran a third experiment using Detector A. This experiment was specifically designed to measure light outputs below 1 MeV, and it used neutron scattering and time-of-flight techniques. The advantage to this approach is that it produced peaks rather than continuous pulse-height spectra. A diagram of the experimental geometry is shown in Fig. 11. A $^{238}\text{PuBe}$ source, which emitted 1.27×10^7 neutrons per second, was placed at the base of a hole drilled to the center of a 457-mm-diameter polyethylene sphere. The resulting beam of neutrons was directed at the new 51-mm by 51-mm detector (Detector A). Some of the neutrons were scattered at 45 degrees with respect to the neutron beam in Detector A; some of those left the detector traveling parallel to the floor, and some of those reached the old 51-mm by 51-mm detector (Detector B), which was located 1 m away (center to center). Due to the kinetics of the reaction, the recoil protons produced

Table 5. Coefficients of a fifth degree logarithmic polynomial fit to the light output data obtained from monoenergetic neutrons.

Coefficient	Value
A_0	-4.51041E-1
A_1	1.57165
A_2	-3.39113E-4
A_3	-6.19874E-2
A_4	1.21722E-2
A_5	4.28494E-4

Figure 9. Electron energy as a function of the neutron energy that produces the same amount of light in NE 213. Measured for three detectors.

Figure 10. Light output of NE 213 as a function of neutron energy. The shape of the data points represents the uncertainties in the energy and light. The dotted curve is a fifth-degree log polynomial fit to the data.

Figure 11. Diagram of the experimental setup used for the scattering, time-of-flight experiment.

by these neutrons in Detector A also recoiled at 45 degrees. For this scattering angle, the recoil neutron and recoil proton both have an energy equal to one-half the energy of the incident neutron. The energy of the scattered neutrons, and thus the protons, was determined by measuring the time the scattered neutrons took to travel from Detector A to Detector B.

The electronics used for this experiment are considerably different than those used for normal spectrum measurements. As shown in Fig. 12, anode signals from the detectors went to two PSD-5010 pulse-shape discriminators (PSDs) (Link Systems, High Wycombe, Bucks., England) where they operated constant-fraction discriminators. The constant-fraction discriminator outputs were available from these PSD units as the threshold (Thr) signal. These outputs provided the start and stop signals for a time-to-amplitude converter (TAC). The neutron identification signals (n) from the PSD units went to a coincidence circuit with a 250-ns resolving time. The output of the coincidence circuit provided gating pulses for the two inputs of an ND-620 multiparameter analyzer (not shown on the diagram). One analog-to-digital converter (ADC) input was provided by the TAC; the other came from the eighth dynode of Detector A by the same preamplifier and linear amplifier used for spectrum measurements. The amplifier output signal had to be delayed somewhat to keep it coincident with the TAC output.

When a coincidence was detected in the pulses from the two detectors, both the pulse height produced in Detector A and the flight time of the neutron between the detectors were recorded. The analyzer was operated in the dual-parameter list mode so that both pulse height and flight time could be recorded in 256 increments. This was equivalent to a dual parameter measurement of 65,536 channels. Available memory limited the measurements to 4,096 events at a time, after which the data were transferred to magnetic tape and another run begun. During calibrations, the gamma identification signals (g) from the PSD units replaced the neutron signals as the inputs of the coincidence circuit.

We chose the PuBe neutron source because 1) its spectrum included neutrons at twice the energy of interest, and 2) its yield was not so strong as to produce an excessive count rate in Detector A. The small solid angle involved in the scattering meant, however, that data had to be taken for 40 days to get acceptably low uncertainties. To ensure stability over this long period, the pulse-height and time channels were calibrated every morning. The

Figure 12. Block diagram of the electronic components used for the scattering, time-of-flight experiment.

pulse-height calibration procedures were the same as those used for high-gain neutron spectrum measurements. Pulse-height calibration data were reduced using a program developed for spectrum measurements. To calibrate the TAC, we used the coincident pulses (produced by a ^{22}Na source) coupled with varied cable lengths between the discriminator outputs and the time-to-amplitude converter inputs. Centroids of the data from the cable runs were obtained using an algorithm built into the MCA. Straight lines were then fit to both sets of data using a linear least-squares program. The dual parameter data were transferred to a computer where they were sorted into bins according to the calibration data. These bins were associated with the flight times of neutrons with energies of 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, and 2.0 MeV. A time spread equivalent to an energy spread of 5% was allowed.

The rebinning yielded asymmetric peaks in the pulse-height data, so a second derivative technique (rather than a centroid calculation) was used to deduce the location of the peaks. A Gaussian-weighted, multi-point derivative with a sigma of three channel widths gave the best results. These data are given in Table 6 and are compared to the polynomial fit of the accelerator

Table 6. Light output as a function of proton energy. Deduced from a scattering, time of flight experiment.

Proton energy (MeV)	Light (light units)
0.200 ± 0.010	0.081 ± 0.001
0.300 ± 0.015	0.090 ± 0.002
0.400 ± 0.020	0.147 ± 0.002
0.500 ± 0.025	0.213 ± 0.007
0.600 ± 0.030	0.287 ± 0.009
0.700 ± 0.035	0.359 ± 0.011
0.800 ± 0.040	0.426 ± 0.016
1.000 ± 0.050	0.735 ± 0.038
1.200 ± 0.060	0.834 ± 0.029
1.400 ± 0.070	1.222 ± 0.024
1.600 ± 0.080	1.317 ± 0.035
1.800 ± 0.090	1.706 ± 0.070
2.000 ± 0.100	1.910 ± 0.012

data in Fig. 13. The differentiation and the small amount of data obtained, even in 40 days, combined to produce large uncertainties, as indicated by the size of the ellipses in the figure. Results above 1 MeV are not reliable, but below that the data are reasonably good and agree with the accelerator results.

In Fig. 14, our monoenergetic neutron data (shown as the curve produced by the log polynomial fit) are compared to the widely used data of Verbinski et al.³⁶ There is a significant difference below 1 MeV, which is shown more clearly in Fig. 15. This figure shows a comparison of our data, and its fit, to their data. Uncertainties in our data are reflected by the size and shape of the ellipses. One reason for the disagreement is that their gamma-ray calibrations used only the upper Compton edge of ²²Na and assumed a linear response with a zero intercept. Applying our nonzero intercept to their calibration produces considerably better agreement. There may also be other reasons for the disagreement, as problems with the Verbinski et al. low energy data have been noted by others.⁴¹

Light Output as a Function of Time

Most crystalline organic scintillators and some deoxygenated liquid scintillators produce light with multiple components that decay at different rates. The ratio between the light in the long and short components of the light is a function of the stopping power or linear energy transfer (LET) of the particle producing the light. This variation in the pulse shape makes it possible to separate the pulses produced by gamma rays from those produced by neutrons. Pulse-height discrimination against gamma-ray-produced signals is not usually practical, because the electrons produce more light per energy deposited in the scintillator than recoil protons do. Without pulse-shape discrimination, low energy measurements of neutrons with an organic scintillator would be severely limited by the gamma-ray response.

Although there may be many components in the decay, the light produced in the NE 213 by charged particles is usually expressed as the sum of two exponentials. This can be written for time in nsec, $L(t) = A e^{-t/b} + C e^{-t/d}$. There are many published values for the constants A, b, C, and d. Three papers that illustrate the range of the values are by Sjolen, Roush et al., and Kuchnir and Lynch.⁴²⁻⁴⁴ Their results are compared in Table 7. Table 7 also includes the areas of the fast and slow components (normalized to a total

Figure 13. NE 213 light output as a function of neutron energy data from scattering, time-of-flight experiment.

Figure 14. NE 213 light output as a function of neutron energy, with results compared to data of Verbinski et al.

Figure 15. NE 213 light output as a function of neutron energy (for energies below 1 MeV), with results compared to data of Verbinski et al.

Table 7. Comparison of different fits to light as a function of time for NE 213.

Authors		Coefficients				Fast area	Slow area	Ratio
		A	b	C	d			
Sjolen	γ	0.165	3.36	0.0180	24.6	0.556	0.444	1.25
	n	0.134	3.94	0.0100	47.1	0.527	0.473	1.11
Roush Wilson Hornyak	γ	0.124	5.2	0.00334	107	0.643	0.357	1.80
	n	0.0959	5.6	0.00336	138	0.537	0.463	1.16
Kuchnir Lynch	γ	0.176	5.3	0.000292	237	0.931	0.0692	13.5
	n	0.123	5.3	0.00124	281	0.651	0.349	1.87

area of one) and the ratio between them. The ability to separate neutron and gamma-ray interactions depends upon the fast-to-slow ratios being different for the two radiations. Our experience is in line with the Roush et al. ratios, although Gatti et al. obtained results consistent with the Sjolen data.⁴⁵ A large number of techniques have been proposed to use these differences to discriminate between neutrons and gamma rays. The first practical circuits were reported by Brooks.⁴⁶

LIGHT PIPE

In the widely quoted 1968 paper by Verbinski et al., there is a reference to a light pipe placed between the scintillator and the photomultiplier to reduce the variations in light collection that occur over the length of the scintillator.³⁶ These variations can significantly decrease the resolution of the detector when the entire volume is irradiated. This requirement is often ignored. There are no light pipes in the detectors we purchased completely assembled, and light pipes are usually omitted by people who build their own detectors. More recently, in 1979, Klein and Scholerman published details of Monte Carlo calculations of the effects that light pipes have on the resolution of liquid scintillators.⁴⁷ The light pipe they built on the basis of their results was quite complex. After studying their results, we

decided that a less sophisticated light pipe of the right length would produce similar results. To test that theory we designed the experiment diagrammed in Fig. 16.

The 51-mm diameter by 51-mm high NE 213 scintillator cell (Nuclear Enterprises, Model VH1), which subsequently became part of Detector A, was irradiated by a ^{22}Na source with the gamma rays collimated into a plane perpendicular to the cylindrical axis of the cell. The collimator consisted of two 102-mm-square by 51-mm-thick lead bricks separated about 3 mm. To simplify the experiment, only three planes through the detector were irradiated: one near the bottom (next to the photocathode), one at the middle, and one near the top. The top and bottom positions were located far enough from the ends of the cell to guarantee that the diverging beam would remain within the sensitive volume. Using ^{22}Na allowed the effect to be tested at two energies simultaneously. Figure 17 shows the pulse-height spectra, recorded with no light pipe in place, for the top and bottom irradiation positions.

Seven 51-mm-diameter polymethylmethacrylate light pipes were used. They were 3.2-, 6.4-, 9.5-, 12.7-, 15.9-, 19.1-, and 25.4-mm thick. (Except for the last, these increase in 3.2-mm increments.) Silicon grease was used for the optical coupling between the scintillator cell and the light pipe and between the light pipe and an RCA 8850 photomultiplier tube. Measurements of the pulse-height spectra were made by sequentially irradiating the bottom, middle, and top positions on the cell for each light pipe thickness. The signal was taken from the tenth dynode of the PMT and amplified with a charge-sensitive preamplifier and a linear amplifier. Measurements were made in a light-tight box that had to be opened to change light pipes or irradiation positions. The light level in the laboratory was reduced during these changes to minimize problems with PMT stability. Because the high voltage on the PMT had to be turned off for each change, the system was allowed to stabilize for at least two minutes after each change in light pipe or irradiation position.

Data were recorded for ten minutes at each point to obtain at least 2000 counts in the peak in the Compton distribution produced by the 1.27 MeV gamma rays from the source. A pulser was used to calibrate pulse height to an arbitrary voltage scale. These calibrations provided a means of compensating for fluctuations in gain and analog-to-digital converter zero drift. Fluctuations in PMT gain that might have been caused by the high voltage

Figure 16. Diagram of the experiment used to determine the effect of light-pipe length on detector resolution.

Figure 17. Pulse-height response of scintillator without a light pipe. The detector was exposed to a collimated ^{22}Na source in a plane near the photocathode and opposite it.

cycling could not have been detected by this calibration. Repeat runs were made with the 6.4-, 12.7-, and 19.1-mm light pipes to study photomultiplier drift and to test the reproducibility of the light coupling and source placement. The percentage differences for the repeated runs were within the counting statistics; however, the points fell consistently lower than the original data, indicating the possibility of some drift. The maximum uncertainty for any of the points was 7%.

Because the resolution obtained at any given position depended upon light pipe thickness, some procedure had to be used to compensate for resolution in order to compare the pulse heights measured for the different cases. We chose the techniques given by Dietze for deducing the position of the Compton edge.⁴⁰ As we have noted, however, no such technique for deducing the location of the edge from measured features of the Compton distribution (such as peak and half height) is consistently satisfactory.

The amount of light reaching the photocathode decreases as the light pipe thickness is increased, so changes in pulse-height uniformity become more obvious when a normalization is used. In Fig. 18, the location of the Compton edges for each energy, as a function of light pipe thickness, have been normalized to the values obtained at the middle of the cell for the same energy and thickness. Uniformity of response continued to improve up to the maximum tested light pipe thickness of 25 mm. The effect of the 25-mm light pipe is also shown in Fig. 19, which, except for the inclusion of the light pipe, shows data similar to that shown in Fig. 17.

These data imply that the reason that pulse-height uniformity is improving is because light from the bottom of the scintillator is more apt to leak through the sides of the light pipe than light produced higher in the cell. Painting the light pipe with black paint might increase this effect and decrease the length of light pipe required. Figure 20 shows that this is not the case. Only four increments were run, because the black paint greatly increased the attenuation of the light pipes. The increase in the uniformity of the response was, however, essentially the same as that obtained with the light pipes with polished sides. Conversely, light pipes are often enclosed in aluminum foil to improve their transmission. A test was made of the effect of a reflector on the ability of the light pipe to improve pulse-height uniformity (the results are shown in Fig. 21). As might be expected, the reflector-enclosed light pipes were not as effective as the bare light pipes at improving the uniformity of the pulse-height response.

Figure 18. Normalized pulse height as a function of position, energy, and length using bare-sided light pipes. The normalization was made to the data obtained at the mid-plane of the detector. Lines represent trend of data for bare-sided pipes.

Figure 19. Pulse-height response of scintillator with a 25-mm-long light pipe.

Figure 20. Normalized pulse height as a function of position, energy, and length using black-sided light pipes. Lines represent trend of data for bare-sided light pipes.

Figure 21. Normalized pulse height as a function of position, energy, and length using reflective-sided light pipes. Lines represent trend of data for bare-sided light pipes.

The effect of the light pipe on the overall resolution of the detector was determined from the pulse-height spectra produced by an uncollimated source as the light pipe thickness was varied. We used the method of Dietze to obtain values of $\frac{\Delta L}{L}$ from the measured maxima and half heights. These are plotted as a function of light-pipe thickness in Fig. 22. Data for light pipes thicker than 25 mm were obtained by combining two shorter light pipes. Because the resolution of a scintillation detector is a function of the amount of light reaching the photocathode, and because light decreases as light-pipe length increases, we were surprised to find that the increasing uniformity of light collection remained more important than the amount of light collected for light pipes up to 38-mm thick. The relative decrease in the collected light, as a function of increasing light-pipe thickness, is shown in Fig. 23.

As a further test, the response at the bottom, middle, and top of the integral 51-mm and 25-mm detectors was measured using the collimated source. As previously noted, these detectors were supplied without light pipes. In each case, the response at the bottom was 10% greater and the response at the top was 8% less than that at the middle.

These experiments with light-pipe design showed that a liquid-scintillator, fast-neutron spectrometer should include a light pipe between the cell and the PMT and that sides of the light pipe should be polished rather than painted or enclosed in an aluminum reflector. The two newest detectors assembled here include 25-mm long, 51-mm diameter glass light pipes. These light pipes are made of glass because plastic light pipe would contain a large amount of hydrogen that could scatter neutrons into the scintillator. The light pipes are mounted to the cell and PMT with a transparent silicone potting compound. Ideally, nothing should touch the side of the light pipe. This arrangement would not be very robust, however, so a spider, made of heavy brown thread, is used to give the light pipe extra lateral support. A possible disadvantage of glass is discoloration while it accumulates neutron dose, but this is not expected to be a major problem.

PHOTOMULTIPLIER TUBE

The photomultiplier tube is a major component of the detector. Those used with our detectors were described briefly in the section on scintillators

Figure 22. Relative pulse-height resolution as a function of light-pipe length and energy.

Figure 23. Light transmission as a function of light-pipe length and energy. Normalized to values obtained with no light pipe.

in use at LLNL, but a few comments will be made here on the general requirements for a PMT to be used with an NE 213 detector.

The tube should have a sensitivity as a function of wave length that is a reasonable match to the light produced by the scintillator. Like most organic scintillators, the NE 213 emits predominantly blue light, which is satisfactorily detected by a PMT with a bi-alkali photocathode. Such photocathodes also have relatively high sensitivities and low noise.

To discriminate between electrons and protons on the basis of the decay of the scintillator pulses, the PMT must be capable of producing anode pulses that follow the input signals. This requirement implies the use of fast, focused-dynode structures and limits the use of slower dynode configurations such as Venetian blinds. The anode should also be capable of driving a coaxial cable. For our applications, that would require a 50-ohm anode impedance.

Ideally, the diameter of the photocathode should match that of the detector and light pipe. This is easily accomplished for detectors with a 51-mm diameter, but suitable PMTs may not be available, especially for larger detectors, in which case a tube with poorer qualities may have to be used.

RESPONSE OF PMT AND LIGHT PIPE TO NEUTRONS AND GAMMAS

A basic assumption is that the recorded pulse-height spectrum is produced entirely by the scintillator. Many plastic and glasses will scintillate when irradiated, so we made measurements to determine the contribution of neutron and gamma rays (interacting directly with the light pipe or PMT) to the pulse-height spectrum.

The newest 51-mm by 51-mm detector (which has the cell that allows it to be operated pointing down) was initially assembled using silicone grease (rather than the plotting compound) between the PMT, light pipe, and cell. It was then calibrated with ^{241}Am , ^{22}Na , and ^{137}Cs sources to set the high voltage and linear amplifier gains at settings similar to those used for a high gain (low energy) measurement. A $^{238}\text{PuBe}$ source was then used to set the operating parameters of the pulse-shape discriminator. Neutron measurements were then made using PuBe and PuLi sources. These two sources were chosen because of the large difference in their average energies.

Next, the detector was assembled with two layers of aluminum foil between the cell and the light pipe, and a second set of neutron measurements was made. Finally, similar measurements were made with the detector assembled with the aluminum foil between the PMT and light pipe.

Data for these three runs for both sources were summed over pulse heights equivalent to neutron energies from 0.4 to 0.5 MeV, which is normally the lowest usable bin. The combined contributions from interactions with the light pipe and PMT were 0.04% and 0.36% of that from the scintillator for the PuLi source and PuBe source, respectively. The contributions from the PMT alone were 0.01% for PuLi and 0.09% for PuBe. None of these pulses fell in the next higher energy bin. These results were obtained with the pulse-shape discriminator set to give approximately 1% gamma leakage. At settings that gave a 2% gamma leakage, the PuBe source gave a 1.06% neutron equivalent response from the light pipe and PMT in combination, and 0.25% from the PMT alone. These results show that direct interactions with the light pipe or PMT are probably not important in normal measurements.

3. ELECTRONICS

All of the detectors use the electronics system shown in Fig. 24. Appropriate changes must be made in the instrument settings and PMT dynode-bias circuits for each detector. The major components were specifically chosen to be compatible with the nuclear instrument module (NIM) standards to get the flexibility afforded by their uniform size, power, and signal requirements. Most were obtained commercially, but the PMT dynode-bias circuits, the preamplifier for the linear signals, and a special live-time clock were designed and built at LLNL.

PHOTOMULTIPLIER TUBE DYNODE BIAS CIRCUIT

The first light-output data obtained using monoenergetic neutrons indicated a loss of linearity in the response of the detectors for neutron energies greater than 6 MeV. This was substantiated by studying the position of the double escape peak produced in the scintillators by the 6.14 MeV oxygen de-excitation gamma ray from the $^{19}\text{F}(p,\alpha\gamma)$ reaction in the LiF neutron

Figure 24. Diagram of the electronic components used for neutron spectrum measurements with an NE 213 detector.

target. The escape peak was found considerably below where the calibrations, made using the lower energy sources, predicted it should be. Tests made with a pulser showed that the preamplifier and amplifier were operating properly. Assuming the light output of the scintillator did not saturate at higher energies, we concluded that the PMT or its dynode bias circuit were the possible sources of the problem.

We were able to borrow a small $^{13}\text{C}(\alpha,n)$ source, which is also a source of 6.14-MeV gamma rays.⁴⁸ A tube base that could be easily modified was built for the integral 51-mm by 51-mm detector.

To determine the effectiveness of each modification to the PMT base, we compared the measured pulse height of the double-escape peak (produced by the 6.14-MeV gamma rays) to a prediction of that pulse height. The prediction was obtained by extrapolating from a linear least-squares fit to the pulse heights of the three Compton edges produced by ^{207}Bi . An uncertainty for the calculated pulse height of the double escape peak was determined from the least-squares fit. The original tube base produced a response from the 6.14-MeV gamma rays significantly below the prediction. Increasing the current through the circuit did not correct the problem, nor did obtaining the linear signal from a dynode nearer to the cathode.

The current required by the dynodes between the anode and the dynode used to obtain the linear signal seemed to impair the signal. We tested this assumption by operating the dynodes between the cathode and the linear output with one high voltage supply and the dynodes beyond that point with a second supply. With this arrangement, the measured and predicted values for the escape peak agreed within the uncertainty involved in the prediction. Using two high voltage supplies, however, is not practical.

Reiter and Stengel published plans for a bias circuit that provides parallel circuits from the high voltage supply to the low current and high current dynodes.⁴⁹ We built a similar circuit, which gave good linearity, but the high power consumption caused significant heating of the PMT with a resulting loss in stability. The high currents required for adequate stability can also exceed the capabilities of readily available high voltage supplies.

We reduced the power consumption by using transistors (rather than smaller resistors) to lower the impedance of the divider.⁵⁰ Fig. 25 shows a diagram of the circuit we use with 8575 or 8850 type tubes.

Figure 25. Schematic diagram of the dynode bias circuit used for 8875 and 8850 photomultiplier tubes.

Actually, the required linearity is maintained by the charge stored in capacitors connected to the dynodes. The transistors provide a low impedance circuit to recharge the capacitors. Smaller capacitors, in the base circuits of the transistors, accommodate the resulting surges in base current.

With this circuit, we obtained a linear response for electron energies from 0.1 to 5.1 MeV. The light produced by electrons in this energy range is the same as that produced by neutrons between 0.6 to 9.2 MeV. Unfortunately, it is not possible to test the performance of the system for light outputs equivalent to neutron energies above 10 MeV. To produce the same light as a 20-MeV neutron would require a source of 15-MeV gamma rays. The maximum current drawn by this circuit is 5 mA with -3000 volts applied. Normal measurements use voltages below 2100 V and currents less than about 3 mA. The six watts dissipated warms the circuit, but this has not caused stability problems.

It is important that the bypass capacitors from the final two dynodes be grounded to the shield of the anode signal cable so that the transmission-line characteristics of the dynodes will provide a 50-ohm anode impedance. We used ceramic capacitors because they are more compact and have the low inductance needed for the large currents and fast pulses encountered. Because ceramic capacitors produce noise when the voltage is first applied, some other type of capacitor would be used if more space were available. Fortunately, the noise decreases the longer the voltage is applied. The high voltage zener diodes can also be a source of noise, but this can be minimized by selecting quiet diodes.

Any shield surrounding the PMT must be maintained at cathode potential to prevent leakage currents that could produce noise or damage the tube. This can be a safety problem when a direct connection to the anode is used, because this places the cathode at a negative high voltage. Fortunately, the shield does not draw significant current, so it can be maintained at cathode potential via a resistor large enough to prohibit dangerous currents.

HIGH VOLTAGE SUPPLY

Many available high voltage supplies combine the required voltage range, current capability, stability, low noise, and NIM packaging. The range of voltages required depends upon the detector used and the energy range

measured. For example, our detectors that use 8875 or 8850 PMTs are operated at -1600 to -1700 volts when the maximum energy to be measured is 20 MeV; they are operated at -2000 to -2200 volts when the maximum energy is 2 MeV. The PMT used with the large diameter detector is run at lower voltages. Even with our transistorized tube bases, bias currents up to several mA are needed for linear high-count-rate and large-pulse response. Stability is needed for high voltage supplies used with PMTs, because gain varies as a power function of the high voltage. The exponent of the power function depends upon the type of PMT. For the 4525, the exponent is 6; for the 8757, 10; and for the 8850, 14. This sensitivity to the applied voltage also makes a low-noise power supply a necessity. We use a Tennelec model TC-951. It has a voltage range from 10 to 3000 volts (positive or negative) at currents up to 10 mA. Regulation is better than either 0.001% or 3 mV, and the noise is 15 mV peak to peak. These should be considered minimum specifications for this application. This supply has a feature that we have found particularly useful; the fine voltage control covers a 1000 V range, so it is possible to go from low to high gain settings without having to change the coarse voltage adjustments. This reduces the strain on the PMT and the base.

PULSE-SHAPE DISCRIMINATOR

An effective pulse-shape discriminator (PSD) is required for the successful use of an organic liquid scintillator as a fast neutron spectrometer. Even though a large number of papers have been published on PSDs, only a limited number of units are commercially available. The ideal PSD unit would operate properly down to low neutron energies, preferably 100 keV or less. It would have a large dynamic range so that a minimum number of measurements would cover the energy range of interest. Simplicity of setup and operation, stability, and high count-rate capability are also important. Despite published claims, no one unit meets all of these requirements. We chose the Link Systems PSD-5010, which is based on the design published by Adams and White.⁵¹ Although this is the best commercially available PSD unit we have used, it has a number of limitations and disadvantages, including a high price. Also, the British supplier has been reluctant to provide adequate information to users.

Positive attributes of this unit are ease of setup, good stability, and ability to handle high count rates. It was designed for use with time-of-flight measurements, so it has good timing capabilities. The fast circuits, however, require considerable power. The unit requires positive and negative 6 volt power, which are NIM standards but are not included in all power supply bins. The unit has a built in pulse-pile-up rejector that works well but causes an increase in dead time. We have also found that the unit creates timing errors when input pulses exceed its upper-level discriminator setting, as is the case during most high gain measurements. These timing errors produce false neutron identification signals that occur after the peak of the signal from the linear amplifier. To overcome this problem, we have found it necessary to operate the unit with the display enabled. This delays the spurious neutron identification signals until after the end of the amplifier pulses, but further increases the dead time. These spurious signals occur even when care is taken to keep the input pulses below 5 V, as is recommended by the manufacturer.

The display is one of the unit's strong points, since it greatly simplifies setting the controls. Separate positive output signals are available that identify the input pulse as a gamma ray or a neutron. The gamma-ray signal is a convenience during pulse-height calibrations. Unfortunately, these signals cannot be transmitted through long cables without the attenuation making them too small for use as standard NIM positive inputs.

There are several other problems with this PSD unit. A direct connection is needed between the unit and the PMT; thus, no blocking capacitor can be used, and the PMT must be operated with the anode at ground potential. The input of the PSD unit has a 50-ohm impedance, which makes it difficult to use a PMT that does not have a 50-ohm anode impedance. Because long cables between the PMT and the unit degrade performance, the unit must be operated near the detector. Moreover, the dynamic range of this circuit is not sufficient to cover the 0.5- to 20-MeV energy range of interest in a single measurement. We have found it necessary to make measurements in two increments, one from 0.5 to 2 MeV and the other from 1.5 to 20 MeV. Routine measurements below 0.5 MeV have not been possible.

PREAMPLIFIER

Linear signals are extracted, as positive current pulses, from the eighth dynode of the PMT (seventh dynode on the 4525). The pulses are integrated, by a charge-sensitive preamplifier designed at LLNL (LE 13965-1), to make them long enough for proper shaping by the linear amplifier. Commercially available preamplifiers could be used, provided they meet some basic requirements. Ultra-low noise is not necessary, but the preamplifier must be able to amplify positive input signals and have good linearity over a wide dynamic range. The unit should use standard NIM power supply voltages. For compatibility with the linear amplifier, the output pulse of the preamplifier must have a rise time on the order of 0.1 microsecond and a decay time of at least 50 microseconds. An output capable of driving a coaxial cable is also needed. Cables with 50-ohm characteristic impedances are used most often at LLNL.

LINEAR AMPLIFIER

A linear amplifier is required to increase the size of the preamplifier signals to the 8- to 10-volt maximum used by the multichannel analyzer (MCA) that stores the data. Adequate gain, low noise, and good count-rate capability are needed. Exceptionally good overload characteristics are needed, because high gain measurements produce many offscale pulses. A base-line restorer helps provide the necessary high-count-rate and overload capabilities. The amplifier must be NIM compatible.

Developments in nuclear electronics have made it possible to find many amplifiers that meet these criteria. We chose a Tennelec TC-202BLR. Although an older design, this compact amplifier meets or exceeds all of the requirements listed, and it has the advantage of using only a single space in the NIM bin. The TC-202BLR provides a choice of four pulse-shaping time constants. For this application, the time constants should be between 0.7 and 1.0 μ s to accommodate the high count rates that may be encountered. Either unipolar or bipolar output pulses can be used, but the same type should be used consistently. We use unipolar.

One of the features of the pulse-shape discriminator we use is an internal single channel analyzer. It is possible to set the gain of the

linear amplifier so that pulses rejected by the upper-level discriminator of the PSD unit correspond to linear signals within the range of the multichannel analyzer. That is possible because the signals that operate the PSD come from the anode, while the linear signals come from a dynode. The ratio of the electron gain at the anode to that at a dynode is a power function of the high voltage applied to the PMT. Optimum use of the dynamic range of the PSD unit occurs when the upper level discriminator setting corresponds to linear signals that are just off scale on the MCA. Consequently, both the PMT high voltage and the linear amplifier gain must be adjusted when the gain of the detector is changed. Figure 26 shows optimum amplifier gain, as a function of high voltage, for our detectors that use the 8850 PMT.

POWER SUPPLY BIN AND LINEAR GATE

Because the logic signals from the PSD unit cannot be transmitted a large distance to gate a multichannel analyzer, and because the PSD unit must be located near the detector, we operate a high voltage supply, linear amplifier, PSD unit, and linear gate in a small NIM power supply bin (Berkeley Nucleonics Corporation, Berkeley, CA). This bin has positive and negative 6-, 12-, and 24-volt power supplies. A source of ac power must be present near the detector to power the bin and high voltage supply, but this is rarely a problem. The small bin and the modules used in it are shown in Fig. 27.

The ORTEC 442 linear gate located in this bin provides the gating required for pulse-shape discrimination. Output pulses from the linear amplifier provide the linear input, and the neutron or gamma-ray logic signals from the PSD unit provide the gating pulses. The short logic signals are reshaped by the linear gate to hold the gate open for the time needed to detect the peak of the linear amplifier output. Output pulses from the linear gate occur at some time after the arrival of the gating pulses. The length of the delay is adjustable. Normally this unit is supplied with a 93-ohm output impedance, but we modified it to 50 ohms to match our cables. If it were not for the dead time generated by the PSD unit, this system would allow the detector to be located a large distance from the MCA, with only a single coaxial cable connecting them. Such an arrangement can still be used if absolute measurements aren't needed.

Figure 26. Optimum linear amplifier gain as a function of photomultiplier tube anode voltage.

Figure 27. Photograph of portanim with the electronic components used near the detector installed.

Dead time produced by the PSD unit must, however, be taken into account, because it is often greater than that of the analog-to-digital converter of the multichannel analyzer. Fortunately the PSD unit provides a dead-time signal, but it, like the other outputs from this unit, will not drive a long cable. We must, therefore, use an auxiliary cable-driving circuit. This also means that a second cable must be run between the bin and the MCA. The dead time produced by the linear gate never exceeds that of the PSD, so no additional compensation is made for it.

LIVE-TIME CLOCK

To make absolute measurements, complete compensation for dead time must be made. The dead time from the operation of the MCA is usually compensated by the clock circuits in the analyzer. For small signals, the dead time generated by the LINK 5010 PSD circuit can exceed that produced by the MCA, so the analyzer live-time corrections will not be sufficient. We built an external clock that uses an OR gate to combine the dead-time signals from the PSD with those from the MCA so that the longer of the two signals inhibits the output of a 20-MHz crystal oscillator. A diagram of the circuit is shown in Fig. 28. The gated oscillator pulses are recorded on a standard scaler. As a convenience, a third input to the clock is connected to another output from the analyzer that starts and stops the clock with the MCA. If an MCA is used that does not have access to the dead-time signal, it may be possible to accumulate the data in enough channels so the MCA dead time always exceeds the PSD dead time. If this is the case, the MCA internal clock might suffice.

MULTICHANNEL ANALYZER

Almost any multichannel analyzer (MCA) can be used to collect the pulse-height data. The primary requirements are that it be capable of measuring in 512 or more channels and that it accept the output pulses from the linear gate. Absolute spectrum measurements are simplified if it provides an external dead-time signal. Some means of storing the data is needed as is an output for transferring the data to a computer. For measurements in the laboratory, we use a Nuclear Data ND-620 analyzer with an ND-575 analog-to-digital converter (ADC). This ADC has a dead-time signal available

Figure 28. Schematic diagram of the special live-time clock.

which also includes the dead time generated by the computer in the MCA. The ND-620 has a variety of output options such as printer and magnetic tape. Ours also has a communications link that allows transferring data to a computer system for data reduction. In the field, we have collected data with an ND-6 analyzer. We had to make a minor modification to the dead-time signal from this analyzer. The data from this analyzer were transferred to a Hewlett-Packard HP-85 computer for recording and reduction. More recently we have acquired a Canberra CI-10 portable analyzer for field measurements. The live time signal from this analyzer is not readily available, however.

4. DATA-TAKING PROCEDURES

The special capabilities of the PSD-5010 pulse-shape discriminator and the ND-620 multichannel analyzer make it possible to separate and record both the neutron and gamma-ray spectra with a single measurement. Although papers have been published on the use of NE 213 for gamma spectrum measurements, the only gamma-ray measurements we make are pulse-height calibrations.⁵² However, we have found published calculations to be useful for verifying the existence of the double escape peaks produced by carbon and oxygen de-excitation gamma rays. The high voltages, amplifier gains, and pulse-shape discriminator settings we use are specific to our detectors and electronics, so the values given in this paper are not universal. They are included, however, because they may be useful as a starting point for setting up other systems.

ESTABLISHING INITIAL CONDITIONS

The range of neutron energies recorded in a single measurement depends upon the gain, which in turn depends upon both the high voltage on the PMT and the gain of the linear amplifier. Changing the high voltage affects the threshold, rotation, and separation settings of the pulse-shape discriminator. Since these parameters are all interrelated, a consistent procedure is necessary to select them for the neutron energy ranges of interest.

Optimum combinations of amplifier gain and high voltage must be determined for each maximum neutron energy of interest. The relation between

these two parameters can be determined, however, without considering neutron energy. First, a high voltage is chosen that is somewhat above the largest expected to be needed for normal measurements. Because its Compton edge occurs at a light value roughly equivalent to that for a 1.5-MeV neutron, a practical maximum high voltage can be obtained by irradiating the detector with ^{137}Cs and adjusting the high voltage until the signals start to go off scale on the display generated by the PSD-5010. For our newest detectors, this requires about -2200 V.

The gamma source should then be replaced with a PuBe neutron source, and the PSD display should be used to obtain approximate settings for the threshold, rotation, and separation controls. The instruction manual for the PSD-5010 may provide some help for choosing the initial settings. Neutron gated pulse-height measurements are then made to find the amplifier gain setting for which the cut off in the pulse-height distribution (produced by the upper level discriminator of the PSD unit's single channel analyzer) falls just off scale on the multichannel analyzer. This amplifier gain ensures the optimum use of the dynamic range of the PSD unit.

This procedure is repeated as the high voltage is decreased in 100-V steps until the signals from the PuBe source are no longer large enough to go off scale. As shown in Fig. 26, the resulting amplifier gains produce a straight line when they are plotted as a function of high voltage on a log-log scale. Extrapolations to gain settings for high voltages that are too low to produce off scale pulses from the PuBe source can be made using this power function. The overall gain necessary to have 20-MeV neutrons go full scale is in such a region. Similar considerations for selecting the optimum combination of gain and high voltage will apply whenever the linear signals are obtained from a dynode and the PSD signals are obtained from the anode.

Next, gamma-ray calibrations are used to find the exact combination of amplifier gain and high voltage needed for specific neutron energy ranges. With the high voltage at these selected values, the optimum settings of the PSD-5010 threshold, rotation, and separation can be determined by irradiating the detector with a neutron source. Values of these settings must be found for each high voltage used.

The set-up procedures must start by finding the proper threshold setting. This control sets the threshold of a constant-fraction discriminator used to initiate the timing sequence of the PSD unit. Setting the threshold

too low results in lost pulses. To set the threshold, connect a scaler to the THRESHOLD output on the front panel of the unit. This signal is a short, negative-going pulse. As the threshold setting is increased, the count rate will increase for a while and then start to decrease. The point of maximum count rate is normally the optimum setting. If the detector is unusually noisy, it may be necessary to set the threshold high enough to prevent excessive response to the noise. Normally the threshold setting can be set quite high before it rejects pulses that are larger than those discriminated against by a setting of 0% on the lower level discriminator of the single-channel analyzer. It is best to use a setting lower than that because the threshold also controls the pulse pile-up circuits.

The PSD-5010 functions by subtracting a fraction of the total charge in the anode pulse from that portion of the charge in approximately the first 50 nsec of the pulse. An internal control sets the short integrating time. Normally this control will not need adjustment since it is factory-set at an optimum point for NE 213. The fraction of the total charge that is subtracted is adjusted by a front panel control called the ROTATION CONTROL. Gamma rays produce positive differences, and neutrons produce negative differences. Signals are provided from the PSD unit so that these differences can be displayed on the y axis of an oscilloscope as a function of the total charge on the x axis. The resulting display has two lines that diverge with increasing pulse height. Gamma rays produce a nearly straight line since their pulse-height response is essentially a linear function of energy. Neutrons produce a curved line. Adjusting the rotation control rotates these two lines about their apex. Our experience is that a usable rotation setting is one that has the two lines diverge from the apex at approximately equal angles above and below a horizontal reference. Only asymmetries that increase the angle between the neutron line and the horizontal should be used.

Once the threshold and rotation are set, the optimum separation can be found. The separation control moves the entire display up or down on the y axis. Internally, the control adjusts a dc bias on two voltage comparators set near zero volts, one of which triggers for negative-going pulses (neutrons) and the other for positive-going pulses (gamma rays). The separation control affects the amount of gamma contamination in the neutron signals. At low pulse heights, it may be unclear whether a signal was produced by a neutron or a gamma ray. To obtain maximum discrimination

gamma-ray outputs of the PSD when the detector is irradiated with a gamma-ray source, it is possible to determine what fraction of the gamma signals are leaking into the neutron channel for a given separation setting. The leakage will be greatest in the channels near the cutoff caused by the low level discriminator of the PSD unit. We generally use separation settings that give between 1 and 5% leakage. Decreasing the leakage increases the size of the minimum neutron pulse that will be accepted, so some optimization is needed depending upon the application.

LOW GAIN SETTINGS AND PROCEDURES

Our low gain setting is designed to measure neutrons with energies up to 20 MeV. Due to the nonlinearity of the light output, the multichannel analyzer must accumulate data in at least 511 channels in order to record the data produced by neutrons between 0.95 and 1.05 MeV in at least one channel. To accommodate the resolution of the detector, the photomultiplier high voltage and linear amplifier gain are set to put into Channel 511 those pulses that occur at 1% of the total height of the upper edge of the distribution produced by 20 MeV protons. For our newer detectors, pulses produced by an exactly 20-MeV proton would then fall in Channel 493. This calculation is based on a fit to the resolution (obtained for Compton scattered electrons) of the form

$$\text{FWHM} = A + \frac{B}{L} + \frac{C}{L^2}$$

where

A, B, and C = constants,

L = the light value.

To meet this gain requirement, we operate the new 51-mm by 51-mm horizontal/up detector at a high voltage setting of -1670 V with a linear-amplifier, coarse gain setting of 50 and a fine gain setting of 0.790. The PSD-5010 rotation setting is directly related to the length of the anode cable. We use an

threshold setting is 14.0%, the separation 47.0%, and the rotation 25.0%. The lower- and upper-level discriminators are operated at 0% and 100%, respectively. Channel 14 is the lowest channel in which usable data are obtained equivalent to a neutron energy of about 1.5 MeV. The separation and rotation settings are chosen so that about 1% of gamma-ray signals leak into this channel.

The detector is located relative to the source by measuring the distance to the midpoint of the height of the cell; the midpoint is marked on the can for the newer units. After allowing at least 30 minutes for the PMT and dynode bias circuit to stabilize, pulse-height calibrations are made using gamma-ray sources. For these measurements, the gamma output signal of the PSD unit is connected to the logic input of the linear gate. At low gain, several sources are used in order to obtain a number of data points to decrease the uncertainty in the extrapolation needed to reach pulse heights equivalent to 20-MeV neutrons. We always use ^{207}Bi , which produces three gamma rays that are well separated in energy, and ^{22}Na , which produces two gamma rays. When possible, we use the carbon de-excitation gamma rays from a PuBe neutron source. If this source is not available, we add another low energy point from ^{137}Cs . At this gain setting, the lower, middle, and upper half heights of the Compton distributions from ^{207}Bi should occur near Channels 15, 34, and 60, respectively. The ^{22}Na low and high half heights should occur near Channels 13 and 41, and the ^{137}Cs half height near Channel 19. The double escape peak from the PuBe gamma ray should be near Channel 128, and the half height of the upper edge of distribution should be near Channel 167. Data are accumulated until there are at least 1000 counts above background at the half height of the least abundant edge or in the double escape peak. For our sources, this requires about five minutes.

Upon completion of the pre-run gamma-ray calibrations, the neutron signal from the PSD unit is connected as the logic signal for the linear gate. Neutron measurements are continued until good statistics are obtained, until time is no longer available, or until the data in the minimum channel reaches the storage capability of the MCA. The latter case may occur rapidly for fission spectra because the data they produce increase exponentially with decreasing pulse height. This limit may prevent the acquisition of adequate

data in the high energy portion of the spectrum. For an absolute measurement, the correct live time must be recorded. The special live-time clock, which ~~includes compensation for the PSD dead-time;~~ needs to be started and stopped simultaneously with the MCA. Our ND-620 MCA provides an external signal when it is acquiring data that can be used to control the clock. In the field, the synchronization must be done manually. The neutron data must be stored because post-run pulse-height calibrations should be made before the data are reduced.

Pulse-height calibrations must be done without neutrons present because gamma rays from the neutron source make it difficult to locate the salient features of the gamma-ray data. So far we have not encountered many neutron fields where the source could not be moved or turned off; however, the spectrometer could be moved to a neutron-free area for calibrations if necessary.

HIGH GAIN SETTINGS AND PROCEDURES

High voltage and amplifier gain settings for the high gain measurements are designed to measure neutrons with energies up to 2 MeV. We use 511 channels for these measurements and the detector resolution results in the light produced by a 2 MeV proton falling in Channel 445. The high voltage required is -2060 V, the coarse gain is 100, and the fine gain is 1.030. Pulse-shape discrimination settings are: threshold 20.0%, separation 43.0%, and rotation 12.0%. The differences of these settings from those at low gain reflect the effect of the increased high voltage. At these settings the minimum channel is 20, which is equivalent to a neutron energy of about 350 keV. The data obtained from the two gain settings normally overlap from 1.5 to 2 MeV.

Fewer points are needed for the gamma-ray calibrations at this gain because available sources span the pulse-height range. We use the peak produced by ^{241}Am at the low end, the half height of the lower Compton edge from ^{22}Na in the middle, and the half height of the ^{137}Cs Compton edge at the top. The expected channels for these features are 38, 252, and 362, respectively. Sufficient data can be collected from our sources in relatively short times. We run for 200 seconds, primarily to allow sufficient time for the manipulations needed between sources. Pre- and post-run calibrations are made.

Data taken at this gain generate considerable dead time in the pulse pile-up rejector of the PSD circuit. Our experience is that the PSD does not function properly if the dead time exceeds 20%. This limits the source strengths we can measure and sets the source-to-detector distances used. In addition, a large portion of the pulses produced by the detector may be larger than the setting of the upper-level discriminator of the PSD unit. This can produce problems because improper pulses may be gated; these improper pulses can in turn result in excess counts at low pulse heights. As previously stated, we have found that we can minimize this problem by operating the PSD in the display mode; however, this increases the dead time and further reduces the acceptable count rate.

Because the neutron data are spread over considerably more channels per MeV at this gain, multichannel-analyzer limitations do not generally limit the time used to accumulate the data. Moreover, the pulse-height data usually decrease slowly with increasing pulse height, so sufficient counts are obtained in the upper channels in considerably shorter times than required for low gain measurements.

TYPICAL PULSE-HEIGHT DATA

Some typical data are presented to illustrate the complicated relationship between the incident spectrum and the pulse-height distribution recorded for an NE 213 detector. We have chosen cases that are representative of both the gamma-ray calibration data and typical neutron spectra.

Gamma-Ray Calibration Data

Gamma-ray data taken at the low-gain setting are different from those taken at high gain. Figure 29 shows a semi-logarithmic plot of the Compton electron distribution for ^{207}Bi at low gain. No total energy peaks are obtained at these energies, so the half heights of the distributions are used as the calibration points. These pulse-height data are compressed and have little detail because of the wide energy range covered at low gain. The other source used to provide similar data at this gain is ^{22}Na , which provides even lower pulse heights. Extrapolating from these data to provide a light calibration for the entire neutron energy range would obviously produce large uncertainties.

Figure 29. Typical pulse-height data produced at the low amplifier gain setting by ^{207}Bi gamma rays.

The considerably more energetic (4.43 MeV) gamma rays produced by a PuBe source are used to decrease the extrapolation. This gamma ray produces a double escape peak from pair interactions as well as the half height of the Compton distribution. Figure 30 shows a typical measurement of this pulse-height spectrum. The escape peak is not prominent on a semi-logarithmic plot such as this. We determine the location of the peak by using a centroid calculation after a background is subtracted using a linear interpolation under the peak. Even this gamma ray produces light that is only about one fourth of that necessary to reach full scale for this neutron energy range, so considerable extrapolation is still required. The 6.13 MeV gamma ray from a PuC source would be somewhat better, but the available source was too weak for routine use. Both PuBe and PuC also produce neutrons, so their gamma rays can be used for calibration only if the PSD unit used provides a separate gamma gating signal.

At high gain, low energy sources are used for part of the calibration. As shown in Fig. 31, the energy of the gamma rays from ^{241}Am is low enough to produce a total absorption peak in the NE 213. The peak is obvious, but some means must be found to compensate for the partial energy depositions that underlie it. We use a technique that subtracts a background by linearly interpolating beneath the peak. The peak itself is found from a centroid calculation.

Figure 32 shows the response to ^{22}Na at high gain, which is the Compton edge from the annihilation gamma rays. This edge occurs on top of the distribution produced by the higher energy gamma rays from the source. Deducing the half height of the edge from these data is straightforward, although some smoothing is normally used before reducing the data. The Compton distribution from ^{137}Cs gamma rays falls on scale at this gain, as shown in Fig. 33. This figure is a good presentation of the details of the pulse-height response of the NE 213 to gamma rays. Notice the response to the 32-keV X-rays at low pulse heights.

Neutron Data

The pulse-height spectrum recorded for neutrons bears little resemblance to the initial neutron energy spectrum. One problem is the nonlinear relationship between energy and light already discussed. Other distortions are covered in detail in later sections. The response to monoenergetic

Figure 30. Typical pulse-height data produced at the low amplifier gain setting by the gamma rays from a plutonium-beryllium neutron source.

Figure 31. Typical pulse-height data produced at the high amplifier gain setting by ^{241}Am gamma rays.

Figure 32. Typical pulse-height data produced at the high amplifier gain setting by ^{22}Na gamma rays.

Figure 13 Typical pulse-height data produced at the high amplifier gain setting by ^{137}Cs gamma rays.

neutrons of approximately 4.5 MeV is shown in a semi-logarithmic plot in Fig. 34. These data were taken to obtain information about the light output, so one of the standard gain settings was not used. The complexity of the response is apparent, although the neutron peak is related to the upper edge of the distribution. Additional complications and distortions occur for higher energy neutrons, as shown in Fig. 35, which depicts the pulse-height data produced by 18.7-MeV neutrons.

It is even harder to relate the pulse-height data to the input for a continuous spectrum. Figure 36 shows the data from a ^{252}Cf source obtained at the low gain settings. These data points are essentially exponential, since they come close to forming a straight line in this semi-logarithmic plot. This shape may not be too surprising for a fission spectrum, but, as shown in Fig. 37, the pulse-height distribution produced by a PuBe source isn't much different. Inflections observed in raw data normally correspond to peaks in the neutron spectrum. The high gain data from both Cf and PuBe look much alike. Figure 38 shows the high gain pulse-height data from ^{252}Cf . These data give few clues about the neutron spectrum that produced them.

5. DATA REDUCTION

GAMMA CALIBRATION DATA

Gamma-ray pulse-height data are transferred from the multichannel analyzer to a computer for storage in a disk or tape file. We have used several computers: a computer-based multichannel analyzer, a desk-top computer, and an LSI-11 (Digital Equipment Corp., Maynard, MA). The positions of the peaks and half heights are located using an interactive BASIC program. The program starts by prompting the user to enter the name of the disc or tape file containing the data. Next it requests the name and approximate pulse-height location of the calibration point to be reduced. The name determines how the data should be reduced and what light value to assign to the calculated channel.

The peaks from ^{241}Am and ^{57}Co are identified as AM and CO, respectively. These names cause the program to branch to a routine that begins by searching for a minimum at a pulse height below that of the

Figure 34. Pulse-height data produced by 4.545 MeV monoenergetic neutrons.

Figure 35. Pulse-height data produced by 18.736 MeV monoenergetic neutrons.

Figure 36. Typical pulse-height data produced at the low amplifier gain setting by spontaneous fission neutron from ^{252}Cf .

Figure 37. Typical pulse-height data produced at the low amplifier gain setting by neutrons from a PuBe neutron source.

Figure 38. Typical pulse-height data produced at the high amplifier gain setting by spontaneous fission neutrons from ^{252}Cf .

approximate peak. Then a point is found at a pulse height greater than that of the peak where a straight line, tangent to the data at that point, intercepts the minimum previously found. This line establishes the background that is subtracted from the data before a centroid is calculated. A light value based upon the name entered is assigned to the centroid.

Compton edges are defined by the following names: NAL and NAH for the lower and upper edges of ^{22}Na ; BIL, BIM, and BIH for the lower, middle, and upper edges of ^{207}Bi ; CS for the ^{137}Cs edge; and CE for the edge produced by the carbon de-excitation gamma rays from a PuBe source. When one of these is entered, the computer branches to a routine that searches for a peak at a pulse height below that of the approximate half height, then it looks at pulse heights above the half height for either a minimum or the last data channel. Data in the peak and the minimum are averaged to determine the half height. To deduce a channel number for the half height, the program interpolates between the channels with counts just above and just below the average. The light value related to the name is assigned to this value. If the approximate half height is greater than 100, the program performs a five-channel smooth on the data before going through the procedure just described.

The double escape peaks from the carbon and oxygen de-excitation gamma rays are given the names C and O, respectively. The program reduces these data by seeking minima in the data at pulse heights above and below that of the approximate peak. A straight line fit between these minima provides a background that is subtracted from the data before a centroid is calculated. As before, the name entered determines the light value assigned to the centroid channel number. The light values for the half height of the carbon de-excitation gamma ray and the double escape peaks were derived by extrapolating from the experimental data obtained at lower energies.

When all of the calibration data for a given neutron run have been reduced, the program fits a least-squares straight line to the results to obtain a slope in channels-per-light-unit and an intercept in channels. The program asks for a name for the file it creates to store the slope values and the intercept values. It also stores the sums required to calculate the uncertainties when channel values are calculated from the fit.⁵³ In addition, the slope, intercept, and related uncertainties are printed.

NEUTRON SPECTRAL DATA

Before discussing the specifics of the techniques we use to reduce the neutron data, we will briefly review the available alternatives. One widely used technique was described by Burrus and Verbinski in which the pulse-height data produced by an unknown spectrum are fit with known spectra obtained by irradiating the detector with monoenergetic neutrons.⁵⁴ This is a powerful technique because the distortions produced by nonlinear light output, multiple scattering, and neutron interactions with the carbon in the scintillator are included in the known spectra and thus are automatically taken into consideration when reducing the data.

Problems associated with this technique, however, decrease its usefulness for radiation protection. Many response functions must be known that should be measured for the specific detector being used. This involves a series of careful measurements that few facilities are equipped to make. An alternative is to use published response functions such as those of Verbinski et al.³⁶ Unfortunately, these particular data were obtained with a different sized detector than is normally used, and the side, rather than the end, of the detector was irradiated. A computer with a large memory is needed to store and manipulate the response matrices. In addition, some means of constraining the fit must be used to prevent negative solutions to the least squares procedures. The constraints can produce oscillations in the unfolded spectrum.

An alternative is the procedure reported by Baldinger, Huber, and Staub in which the neutron spectrum is related to the negative of the slope of the pulse-height data.¹⁷ Several approximations are needed to use this approach for data from organic scintillators because it was originally developed for data obtained from gas-filled counters. The basic procedures were reported by Poole in 1952³³; Broek and Anderson provided more details in 1960.³⁵ These techniques compensate exactly for the nonlinear relation between light and energy. The paper by Broek and Anderson also includes a way to compensate for multiple scattering at low energies and for edge effects at high energies. The distortions produced by neutron interactions with carbon were ignored by Poole and by Broek and Anderson because they only become important at higher energies.

We use a modification of the slope-finding technique that allows small computers to reduce data quickly. This allows data to be taken and reduced in

the field, which is often a necessity for radiation protection measurements. We have restudied the distortions and derived means of dealing with them that are conceptually similar to those of Broek and Anderson, but our methods are numerically different. Since their work involved stilbene crystals that were quite small compared to the NE 213 detectors we use, the differences in our results are not surprising.

Rebinning

Once the linear fit to the pulse-height calibration data is available, the neutron spectrum data can be reduced using another BASIC program. This program first requests the name of the file of the gamma calibration data, then retrieves the slope, intercept, and error parameters. Next, the program requests the name of the neutron data file. If the file was stored as binary data, the file can be opened as a virtual array. This saves memory space but increases running time. Our desk-top computer and the LSI-11 have more memory than the computer-based multichannel analyzer, so data are usually put into a memory array with them, while a virtual array is necessary with the MCA system.

One way to correct for the nonlinear light output is to redistribute the pulse-height data into bins that have a fixed energy width, a procedure suggested by Poole.³³ Rebinning to consistent energies and bin widths yields a number of advantages for combining and comparing data. We rebin using 0.1 MeV increments of neutron energy with the program starting at 0.1 MeV, although obtaining data that low in energy is unlikely. Light as a function of neutron energy is calculated directly from the fifth degree log polynomial or is obtained from a disc or tape file of values previously calculated from the fit. These values are converted into channel numbers using the slope and intercept from the pulse-height calibrations. The resulting channels are seldom whole numbers, so linear interpolations are made at the lower and upper limits of the bin. Data from whole channels between the fractional values are added without modification. The total number of channels used to collect the data is chosen so that the lowest energy bin will include at least one channel; this is done to avoid two interpolations within a single channel. As noted by Miller, more sophisticated interpolation techniques are not needed.⁵⁵

Rebinned data have a statistical uncertainty derived from both the number of counts in the bin and the uncertainty is the width of the bin. The latter

is calculated using the parameters obtained from the fit to the pulse-height calibration data. Errors in the positions of the lower and upper edges of the bin are correlated, which makes the error in the width less than the error in its energy assignment. Whole channels contribute only counting statistics, so the overall uncertainties are somewhat smaller when more channels are involved in the sum for a given bin. This effect occurs in the high gain data for which the 511 channels used are rebinned into only 20 energy groups.

Finding the Slope

Once the data are rebinned, they are differentiated by subtracting the data in a given bin from that in the bin at the next lower energy and dividing the difference by the 0.1 MeV energy difference between the bins. This is the negative of the usual formula for the slope of a straight line, $(Y_2 - Y_1)/(X_2 - X_1)$, because the data reduction formula requires the negative of the slope of the proton-recoil distribution. We rebin data into bins that go from E_n to $E_n + 0.1$. In such procedures the midpoint of the histogram is normally used as the abscissa, so our bins have energies with units of $E_n + 0.05$. The slope we obtain is associated with an energy midway between those of the bins involved which results in energy units of $E_n + 0.1$, but incremented by 0.1 MeV from the original units. Thus our reduced data always start 0.1 MeV above the lowest energy bin obtained from the pulse height data.

It is the area, not just the slope, of the pulse-height distribution produced by the recoil protons that is proportional to the number of incident neutrons. To obtain an area, the slope at a given point is multiplied by the related energy. The number of incident neutrons is obtained by dividing the area by the efficiency and correcting for multiple scattering and edge effects. Our program reads from a file containing the combined efficiency and correction factors, averaged over the bin for each energy,. The complexity involved in calculating the carbon cross sections makes it impractical to calculate these factors each time the program is run. Since our energy bins are always the same, the efficiency and correction factors need to be calculated only once and stored.

Uncertainties in the neutron fluences are based upon 1) uncertainties in the rebinned data and 2) estimates of how well the components in the efficiency equation and the multiple scattering and edge effect corrections are known. The predominant factor is the uncertainty in the multiple scattering correction factors.

Multiple Scattering and Edge Effect Corrections

In an organic scintillator, neutrons can collide with carbon as well as hydrogen and, unless the detector is quite small, there is a good chance that more than one collision will occur before the neutron leaves the detector. Light pulses from the charged particles produced by the multiple scattering of a single neutron occur within such a short time that they produce a single output pulse from the photomultiplier tube. The probability for multiple scattering increases with decreasing neutron energy because the hydrogen cross section increases. After multiple scattering, the number of neutrons deduced from the slope of the data will exceed the number of incident neutrons. In addition, a second peak can occur in the slope at a lower pulse height; this peak is produced by recoil protons from neutrons that have undergone an initial collision with carbon. At an even lower pulse height, the slope may go negative because multiple scattering shifts data from lower to higher pulse heights. For a continuous neutron spectrum, the increase in the pulse height distribution caused by multiple scattering may be decreased by the shifted data from higher energy neutrons.

Multiple scattering decreases as neutron energy increases because the decreasing cross sections result in a greater probability that the neutron will pass through the detector without interacting; however, edge-effect distortion caused by protons that leave the detector without losing all of their energy becomes larger with increasing energy. Increasing detector size decreases edge effects but increases multiple scattering, so an optimum detector size exists for a given energy range.

Most NE 213 detectors are significantly larger than the stilbene crystals for which Broek and Anderson derived their widely used multiple scattering and edge effect correction factors.^{35,56,57} Despite the parameterization for detector size included in the formulas, when we used these factors the measured fluence values below 1 MeV exceeded those in calculated versions of the same spectra. After we had confirmed that the over-response was not caused by an instrumentation problem, we decided that multiple scattering and edge effects should be studied in detail.

As a preliminary test, we used the response functions published by Verbinski et al. as input data for our data reduction procedures.³⁶ These data combine experimental measurements and Monte Carlo calculations and are normalized to one incident neutron. Thus the number of neutrons deduced when

our data reduction procedures are used, without the corrections, should be the multiple-scattering, edge-effect correction factor. At low energies, these results were significantly larger than values obtained from the Broek and Anderson formula (22% larger at 426 keV). While this confirmed our suspicions, we could not use these results with our experimental data because of the different detector geometry and the side irradiation used by Verbinski.

To derive multiple scattering and edge-effect correction factors, we wrote a Monte Carlo program to simulate the interaction of neutrons with an NE 213 detector. The advantages of this procedure over trying to derive the factors from experimental data are: better statistics, no gamma-ray interference, perfect low energy response, and the ability to extract the first collision data independently. Thirty collisions were allowed unless the neutron left the detector or its energy decreased to 1% of the initial value. Ranges were calculated for the recoil protons, and only the energy deposited in the detector was used to calculate the light produced. Elastic and inelastic interactions with carbon were allowed. Two simplifications were used. All scattering was assumed to be isotropic, and all carbon inelastic events were assumed to be n,α reactions. The light produced by the recoil carbon ions and alpha particles was approximated using data for these ions given by Verbinski et al. adjusted to our light units. All of the light produced was summed and converted to an equivalent proton energy for binning. To be consistent with our data reduction procedures, 0.1-MeV-wide bins were used.

Calculations were made for five cell sizes and geometries that matched our detectors. A plane beam of monoenergetic neutrons was assumed incident on the flat end of the cells. Twelve energies were used: 0.5, 1, 2, 3, 4, 5, 6, 8, 10, 13, 16, and 20 MeV. Both the hydrogen single scatter and the multiple scatter data were accumulated and printed out. Enough cases were run during each calculation to get at least 2% statistics per bin in the single scatter results. No effort was made to include the effects of detector resolution. As expected, single scatter results approximated a rectangular distribution and showed significant edge effects at the higher energies, particularly for the smaller detectors. Figure 39 shows the single scatter spectra calculated for the 51-mm by 51-mm geometry. The multiple scatter spectra for the same detector are shown in Fig. 40.

Figure 39. Results of the Monte Carlo calculations of the light-output spectra produced by the single scattering of neutrons in a 51-mm long by 51-mm high NE 213 detector.

Figure 40. Results of the Monte Carlo calculations of the light-output spectra produced by the multiple scattering of neutrons in a 51-mm long by 51-mm high NE 213 detector.

Sharp peaks occur in the multiple scattering results for neutron energies above 6 MeV because of the simplification used for the carbon inelastic interactions. Peaks in the multiple scatter results for lower energy neutrons are due to multiple scattering of the neutrons. These latter peaks occur considerably below the maximum energy since it is the light produced by the charged particles stopping in the detector--not their energy--that is summed, and light production is nonlinear. Separate collisions of a single neutron are normally spaced far enough apart within the detector that the energy deposited will not migrate to the same light producing centers. Thus, each particle can be considered to produce light independently. Light production efficiency is less for low energy protons, so the total light from a given total energy deposited in increments cannot be as great as that produced when the same total energy is deposited at one time.

To study this effect, we made a series of Monte Carlo calculations that assumed complete absorption of the neutron energy in the scintillator. The results are given in Fig. 41. A linear response would yield a symmetric peak at the energy of the incident neutron, but in this case a skewed peak occurs near 80% of the neutron energy. The multiple scattering data show similar effects. This peak depends on the detector because the amount of multiple scattering depends on geometry. The effects of detector geometry on the multiple scatter spectrum are shown in Fig. 42, which compares the five cases for 4-MeV neutrons. This figure shows how multiple scattering increases as either the thickness or the diameter of the detector increases. The smallest detector consistent with the sensitivity required should be used for any given measurement.

Data calculated for each energy and detector combination were reduced with procedures analogous to those used for experimental data, excluding the multiple scattering and edge effect corrections. Linear energy bins and perfect resolution simplified the process. The number of neutrons deduced from the spectrum was divided by the known number used for the calculation. At lower energies, the quotient obtained from the first scatter data was one, as expected. At higher energies, the value was below one due to edge effects. The quotients obtained from the multiple scatter data were greater than one at low energies but coincided with the single scatter values at high energies. Multiple scattering ratios for the 51-mm by 51-mm detector are shown in Fig. 43, which also shows correction factors calculated from the

Figure 41. Results of the Monte Carlo calculations of the light-output spectra produced by the multiple scattering of neutrons in an NE 213 detector with infinite dimensions.

Figure 42. Effects of detector diameter and height on results of the Monte Carlo calculations of the light-output spectra produced in the NE 213 by the multiple scattering of electrons.

Figure 43. Calculated correction factors for multiple scattering and edge effects of monoenergetic neutrons, as a function of neutron energy.

Broek and Anderson formula. The dashed line at 1 represents the perfect case. Ratios obtained from the first scatter data are given for all of the detectors in Table 8. Table 9 gives the multiple scattering ratios.

Below 2 MeV the calculated multiple scattering correction factors are larger than necessary to correct experimental spectra obtained from continuous sources. These factors may be correct for monoenergetic data, but most measured spectra are continuous. To clarify this problem, additional Monte Carlo calculations were made for continuous spectra. The time required for the calculations made it impractical to obtain data with the same quality as for the monoenergetic cases, and only the 51-mm by 51-mm detector was simulated. Three spectrum shapes were used: a Maxwellian representation of the ^{252}Cf fission spectrum; a rectangular spectrum with a maximum energy of 5 MeV; and a trapezoidal spectrum that decreased with a slope of -1, from seven units at zero energy to one unit at 6 MeV. About 2 million hydrogen first scatters were recorded for the Maxwellian, 5 million for the rectangle, and 7 million for the trapezoid. These data were reduced in the same way as were the monoenergetic cases. The resulting multiple scattering ratios for the Maxwellian, rectangle, and trapezoidal cases are shown in Figs. 44, 45, and 46, respectively. All three are shown to emphasize the rough agreement between these data sets. They all show that 1) the compensating factors that occur in a continuous spectrum keep the low energy multiple scattering factors below those obtained from monoenergetic data and 2) the factors don't seem to decrease as fast with increasing energy as the monoenergetic results.

We made another attempt to obtain these correction factors by comparing the results of measurements with a calculation of the spectrum produced by a ^{252}Cf source. We reduced the experimental data without using multiple scattering and edge effect correction factors and then rebinned the data into the energy intervals used for the calculations. Limited resolution, resulting from the relatively small number of energy bins and their width, reduced the value of the factors obtained from this approach. At any rate, this approach did not clarify the problems generated by the Monte Carlo calculations.

Nothing we tried gave an unambiguous derivation of multiple scattering correction factors to use while reducing an unknown spectrum. Therefore we chose to compromise and use the Monte Carlo continuous spectrum results for the values near 0.5 and use the monoenergetic results for values above 2 MeV.

Table 8. Number of neutrons deduced from the Monte Carlo single-scatter spectra when the calculations are normalized to a single neutron.

E	D1	D2	D3	D4	D5
0.5	1.004± 0.010	1.008± 0.011	0.995± 0.011	0.989± 0.011	1.005± 0.010
1	0.989± 0.010	0.999± 0.010	0.991± 0.010	0.995± 0.010	0.996± 0.010
2	1.018± 0.010	1.004± 0.010	0.999± 0.010	0.990± 0.010	0.987± 0.010
3	0.997± 0.010	1.018± 0.010	1.009± 0.010	0.977± 0.010	0.982± 0.010
4	0.999± 0.010	1.002± 0.010	1.003± 0.010	0.986± 0.010	0.964± 0.010
5	0.979± 0.010	1.011± 0.010	1.002± 0.010	0.990± 0.010	0.951± 0.010
6	0.980± 0.010	0.993± 0.010	0.990± 0.010	1.004± 0.010	0.959± 0.010
8	0.983± 0.010	0.991± 0.010	1.011± 0.020	0.982± 0.010	0.920± 0.010
10	0.946± 0.010	1.012± 0.020	0.990± 0.020	1.004± 0.020	0.901± 0.009
13	0.927± 0.019	0.973± 0.020	0.965± 0.020	1.005± 0.020	0.827± 0.018
16	0.879± 0.019	0.944± 0.019	0.926± 0.019	0.953± 0.020	0.769± 0.018
20	0.812± 0.018	0.898± 0.019	0.923± 0.019	0.912± 0.019	0.620± 0.016

Table 9. Number of neutrons deduced from the Monte Carlo multiple scatter spectra when the calculations are normalized to a single neutron.

E	D1	D2	D3	D4	D5
0.5	1.696± 0.014	2.445± 0.019	2.916± 0.020	2.338± 0.017	1.328± 0.012
1	1.221± 0.011	1.414± 0.012	1.485± 0.013	1.413± 0.012	1.121± 0.011
2	1.146± 0.011	1.231± 0.011	1.256± 0.011	1.221± 0.011	1.056± 0.010
3	1.102± 0.011	1.188± 0.010	1.195± 0.011	1.166± 0.011	1.040± 0.010
4	1.096± 0.011	1.163± 0.011	1.173± 0.011	1.152± 0.011	1.014± 0.010
5	1.068± 0.010	1.153± 0.011	1.165± 0.011	1.148± 0.011	0.997± 0.010
6	1.059± 0.010	1.199± 0.011	1.131± 0.011	1.140± 0.011	1.004± 0.010
8	1.060± 0.010	1.095± 0.010	1.121± 0.021	1.097± 0.010	0.958± 0.010
10	1.001± 0.010	1.093± 0.022	1.069± 0.021	1.091± 0.021	0.936± 0.010
13	0.928± 0.019	0.975± 0.020	0.968± 0.020	1.007± 0.020	0.827± 0.018
16	0.879± 0.019	0.947± 0.019	0.927± 0.019	0.954± 0.020	0.770± 0.018
20	0.813± 0.018	0.899± 0.019	0.923± 0.019	0.915± 0.019	0.620± 0.016

Figure 44. Calculated correction factors for the multiple scattering of neutrons with a Maxwellian energy spectrum, as a function of neutron energy.

Figure 45. Calculated correction factors for multiple scattering of neutrons with a rectangular energy spectrum, as a function of neutron energy.

Figure 46. Calculated correction factors for multiple scattering of neutrons with a trapezoidal energy spectrum, as a function of neutron energy.

We thought it would be useful for data reduction to fit these data with a function parameterized for different detector geometries, similar to the Broek and Anderson equation, but we found no reasonable means of performing the parameterization. A term for the edge effect correction could be parameterized, however, with results similar to the comparable term in the Broek and Anderson equation. That term involves the ratio of the proton range divided by a parameter related to the geometry of the detector. We got the best results using the sum of the radius and height for the geometry parameter.

Although an approximation to the physics involved in multiple scattering would seem like a reasonable way to parameterize that data, such is not the case. In fact, the correction factors depend upon how the data are transformed from a pulse-height spectrum, which is nonlinear in energy, to a neutron spectrum, which is linear in energy. The method used to differentiate the data, and the width of the energy bins used also affect how much of the distortion caused by multiple scattering must be included. Thus, our results were not parameterized but were simply fit with the log quadratic function

$$e^{[A_0 + A_1 \ln(E) + A_2 \ln^2(E)]} .$$

Sufficient data existed to obtain the constants in this formula for only the 51-mm by 51-mm detectors, for which $A_0 = 0.257946$, $A_1 = -0.0172768$, and $A_2 = -0.0338539$. Values obtained with this formula are compared with Broek and Anderson values for this size detector in Fig. 47.

Smoothing

Derivatives of experimental data have larger statistical uncertainties than the data have. Although using differentiation formulas that involve smoothing over a number of data points may reduce this problem, we do not smooth until after the slope has been multiplied by the factors necessary to convert it to a neutron spectrum. Efficiency and similar factors applied to data that are already smoothed should include energy weighting. Our approach avoids this problem. We smooth using a Gaussian weighted average, the width of which varies with energy like the resolution of the detector. The uncertainties in the initial spectrum values undergo the same transformation. At the lower and upper limits of the data, the width of the smooth is limited so that all of the data obtained from rebinning and differentiation are kept.

Figure 47. Multiple scattering and edge-effect correction factors chosen for use compared with those derived from the formula of Broek and Anderson.

The factors that determine the width of the Gaussian distribution can be obtained from a file or calculated depending upon computer memory or data-reduction time limitations.

Printout and Storage of Results

The final section of the program prints the results and stores them on a disk or a tape. When the HP-85 is used, a simple plot of the results is part of the printout. Disk files contain the fluence data, fluence and energy uncertainties, a title for the run, the minimum and maximum values of fluence, and the total fluence and its uncertainty. If possible, the disk files are created as binary files to decrease their size and to simplify access by subsequent programs used to process the data further. The tape files produced by the HP-85 contain only the fluence data and their uncertainties.

COMBINING DATA, DOSE CALCULATIONS, AND PLOTTING

Tape or disk files created by the neutron data-reduction program are used as the input for several auxiliary programs, one of which makes a weighted average of data sets taken at different gains or from repeated measurements. Using uniform energy bins greatly simplifies this process. Dose, kerma, and dose equivalent spectra and totals may also be calculated by this program, depending upon the computer. Sometimes a separated program is used to obtain these results. In either case, the results are printed in tabular form and put into additional disc or tape files that use the same format used by the data reduction program. These files are used, in turn, by other programs to prepare plots of the spectra or to rebin the data into the energy intervals used in computations or multisphere results. All of these programs are written in BASIC to allow variations to be used on most small computers.

COMPARISON WITH RESULTS FROM OTHER PROGRAMS

One way to determine if our procedures are sound is to compare our results with those obtained by reducing the same data with other techniques. Our data reduction procedures evolved from those published by Slaughter and Strout.⁵⁷ The capabilities of their program (FLYSPEC) are compared favorably with several others in a paper by Miller and Meyer.⁵⁸ Thus,

comparing our results with those from FLYSPEC gives an indirect comparison with several other procedures. The major difference between FLYSPEC and our program is whether the slope of the pulse-height data is obtained before or after the data are rebinned.

We modified the "slope first" procedures so that the results could be compared directly to those from our "rebin first" program. Primarily this involved using our light output data (and the log quintic fit we use with it) and rebinning the results into fixed 0.1-MeV-wide bins, 0.1 MeV apart. Normally FLYSPEC uses three spline cubics, fit to the light output data of Verbinski et al., and rebins the output data into a fixed number of bins at arbitrary energies. Multiple scattering and edge-effect corrections and smoothing were not used with either program. Smoothing is normally an integral part of finding the slope in FLYSPEC, so omitting it might be questionable; however, the formula we used to get the slope was mathematically the same as the one for minimum smoothing. Our gamma-ray calibration procedures were used in each case, although these do not differ much from those normally used with FLYSPEC.

Comparisons were made using both high- and low-gain data obtained from a bare ^{252}Cf source. The four sets of results obtained, two with each program, are plotted in Fig. 48. To decrease clutter, no uncertainties are shown, but they are large enough to span the differences between the results from the two programs. As shown, the two techniques produce the same results.

During the process of developing the error calculation procedures used in our program, we did a complete comparison of the errors generated by both programs. Once again the two approaches produced similar results, with the techniques we chose giving slightly smaller uncertainties. The difference apparently arises because every energy value used contributes its uncertainty to the total uncertainty and the energy for every channel must be known for the "slope first" technique, while only the energy at the edges of the bins needs to be known for the "rebin first" technique.

Neither of the programs makes assumptions about the resolution of the detector while reducing the data. This may decrease the quality of the results. This problem is discussed in a recent paper by Subbaiah and Natarajan, who describes yet another way of obtaining the slope of the pulse-height data.⁵⁹

Figure 48. Comparison of the results obtained by reducing data from bare ^{252}Cf by differentiating before or after rebinning.

6. TYPICAL RESULTS

The ultimate value of our techniques and procedures must be measured by how well the system makes measurements in the laboratory and in the field and how well the programs reduce the data. Our experience is that it all works quite well. The easiest way to show this is to present some typical results.

MONOENERGETIC NEUTRONS

Results for four sets of monenergetic data are shown in Figs. 49 to 52. They illustrate the performance of the system over the range of energies for which it was designed. These data were gathered as part of the experiments to determine light output as a function of neutron energy; however, the data reduction techniques were modified slightly because the standard gain settings were not used. For example, most of these data were recorded in 255 channels rather than the 511 normally used. Moreover, fewer gamma-ray calibrations were used with these data, which limits the calculation of errors.

Figure 49 shows the spectrum obtained from 0.439 MeV neutrons. This energy is actually just below the lower limit adopted for the spectrometer and data reduction programs. These neutrons were produced using 2.2 MeV protons on a ${}^7\text{Li}$ target with the detector at a 15-degree angle to the beam. This reaction should produce a minimum of gamma rays and no neutrons with other energies. The 0.1-MeV-wide bins limit the details in the results, but even this width is finer than the 40 to 50% resolution of the detector at this energy. The centroid of the peak occurs at 0.701 ± 0.032 MeV. This is considerably higher than the energy of the neutrons, but it is within the limits of the resolution of the spectrometer. The area of the peak is 1.8 neutrons. If the normalization and performance of the spectrometer were both correct, the value obtained should have been one. Difficulties with the normalization make it impossible to determine how much of this error is the result of problems in the data reduction. Because these data were taken to provide light output data, only a minimal effort was made to obtain neutron yields. Negative values in the reduced data below the peak result from the distortions caused by multiple scattering.

These data were also reduced using the program that differentiated the data before they were rebinned. The results obtained were nearly identical

Figure 49. Results obtained by reducing the data produced by 0.439 MeV monoenergetic neutrons.

Figure 50. Results obtained by reducing the data produced by 1.281 MeV monoenergetic neutrons.

Figure 51. Results obtained by reducing the data produced by 4.545 MeV monoenergetic neutrons.

Figure 52. Results obtained by reducing the data produced by 18.736 MeV monoenergetic neutrons.

with those shown, thus the distortions are not the result of the data reduction procedures.

As shown in Fig. 50, the energy is considerably closer to the expected value for the 1.281 MeV neutrons produced by 2.2 MeV protons hitting a tritium target with the detector at 20 degrees. The centroid for this peak is 1.199 ± 0.045 MeV, which is 94% of the expected value and within the limits of detector resolution at this energy. The area of the peak is 0.99 neutrons. These results also show negative values below the peak caused by multiple scattering.

With the energy of the neutrons at 4.545 MeV, as shown in Fig. 51, the performance of the system should be near optimum. The pulse-height data for this case were shown previously in Fig. 34. Multiple scattering and edge effects are minimal around this energy, and the light values are well known. These neutrons were produced by irradiating a deuterium target with 2.3 MeV deuterons with the detector at 45 degrees. Little contamination from gamma rays or other neutrons occurs with this source. The effect of multiple scattering involving a first scattering with carbon shows as the bump on the low energy side of the main peak, and, even for this optimal case, there are some negative results below the peak. The area of the peak is about 1.3 neutrons. Some of the excess is no doubt due to the contribution from the first scatters with carbon, but some may be due to incomplete normalization data.

One last set of monoenergetic results are shown in Fig. 52. They were obtained with 18.736 MeV neutrons produced by irradiating a tritium target with 2.6 MeV deuterons with the detector at 20 degrees. These data demonstrate the problems caused for this type of data reduction by the neutron reactions with carbon, which include both scattering and the production of alpha particles. At this energy, protons produced by neutrons that have first scattered off of carbon produce a distinct peak below the main peak. Several peaks occur at low energies caused by the n,α and $n,3\alpha$ reactions. The small peak between 6 and 7 MeV is probably caused by (d,d) neutrons produced by a small amount of deuterium on the target. The centroid of the main peak is at 18.0 ± 0.6 MeV, which is 96% of the known energy. This discrepancy is partly because only the first 511 or 1023 data channels were used to obtain these results, and some of the peak fell off scale. The area of the main peak

is only 0.25, although no reason is immediately apparent for this large discrepancy. Most of the problem may be due to the limited knowledge of the number of neutrons measured.

CONTINUOUS SPECTRA

Almost all applications of neutron spectrometry to radiation protection measurements involve continuous spectra. It has already been shown that the problems caused by multiple scattering are easier to correct for a continuous spectrum than for a monoenergetic source. Moreover, many of the spectra to be measured do not have a significant number of neutrons with energies above 10 MeV, so the distortions produced by the alpha producing reactions with carbon are not a significant problem. Thus good agreement should be expected between calculated spectra and the results of data that are measured and reduced using the techniques described here.

Plutonium-Beryllium

The neutron spectrum produced when alpha particles interact with beryllium is often presented as a demonstration of the capabilities of a spectrometer or a data reduction process. Such a source was used by Chadwick to identify the neutron⁵; however, α, n sources are not the best means of comparing the performance of spectrometers or data reduction procedures because the spectra depend heavily upon the composition of the source. De Guarrini and Malaroda measured and calculated the spectrum produced by an AmBe source.⁶⁰ They also compared their results with spectra published by a number of workers for a variety of sources. This compilation showed how the spectrum depends on the energy of the alpha particles and on the size and composition of the source.

The α, n sources used at the Standards and Calibration Facility of the Hazards Control Department of Lawrence Livermore National Laboratory vary in their size, but they all depend on alpha particles produced by ^{238}Pu . The energies of these particles are similar to those from ^{241}Am ; thus our sources should produce spectra more comparable to those from AmBe than the more common $^{239}\text{PuBe}$ sources, since ^{239}Pu produces lower energy alpha particles. Our results for a high yield source are shown in Fig. 53. This is one of the sources that can be moved into the irradiation position

Figure 53. Results obtained by reducing the data produced by a large PuBe neutron source. The measurement was made at two meters from the source.

pneumatically.⁶ The intensity of the source required the measurements to be made at two meters. A comparison of this measurement with the calculations of De Guarrini and Malaroda for AmBe, normalized to the same area, is shown on a linear scale in Fig. 54. Considering the finite resolution of the detector and the size of the source, the agreement is quite good. The major difference is that the measurements do not reproduce the peak seen in the calculations near 6 MeV. This is at a point where the calculations for the ground state and the first excited state of carbon overlap, so the size of this peak may be an artifact of the limited angular distribution data used for the calculations. The agreement at low energies is better than might be expected from our monoenergetic results.

Californium

Another neutron spectrum often used for comparisons is that produced by the spontaneous fission of ²⁵²Cf. Such spectra are also somewhat source dependent because of the scattering that can occur as the neutrons leave a large or heavily encapsulated source. Our results for the source in the pneumatic system at the Standards and Calibration Facility are shown in Fig. 55. These measurements also had to be made at two meters.

Because this source is important for calibration of dosimeters and other instruments, a number of researchers have made calculations of the spectrum and the dose produced as a function of the location of the detector within the exposure cell. For our comparison, we chose the results from a Monte Carlo calculation using MORSE and the National Bureau of Standards form for the initial spectrum (Fig. 56). Uncertainties in the measurements are shown as rectangular boxes. The measured data were rebinned to be compatible with the calculations, and an r-squared correction was made to the calculations from one to two meters. Using an r-squared correction for the calculations is an oversimplification since a large number of neutrons are scattered by the walls of the exposure chamber. Thus only an approximate comparison with the measured data is possible. Agreement is poor at low energies. This may represent an over-response in the measurements or a problem with the calculations due to neutron scattering or an improper input spectrum. The NBS spectrum does not include the effects of the size of the source. The calculations do include the effects of the encapsulation necessary to operate the source in the pneumatic system. Similar calculations and the source encapsulation were reported by Prevo.⁶¹

Figure 54. Comparison of the measured PuBe spectrum with a spectrum calculated for an AmBe source.

Figure 55. Results obtained by reducing the data produced by a ^{252}Cf spontaneous fission source. The measurement was made at two meters from the source.

Figure 56. Comparison of the measured ^{252}Cf neutron spectrum with a spectrum calculated for one meter from the source and adjusted to two meters with an r^2 correction.

Neutron spectra produced by the pneumatically operated PuBe and Cf sources at the Standards and Calibration Facility can be varied by ten spherical moderators that can be placed around the sources. These spheres consist of different thicknesses of water, heavy water, polyethylene, or aluminum. The neutron spectra outside all of these moderators have been measured with the NE 213 spectrometer system. An example of the results for the Cf source is shown in Fig. 57, for which the moderator was a sphere that provided 25 cm of moderation with heavy water. Fluctuations in the spectrum that do not occur in the spectrum of bare californium can be correlated to features of the oxygen cross sections. We plan a separate report to present the results of all of these measurements along with results from multisphere measurements.

FIELD MEASUREMENTS

Many of the choices we made in the design of the spectrometer system and the data reduction procedures were predicated on ease of taking and reducing data in the field. Several measurements we made have proven the viability of these choices.

One of our first measurements was of leakage neutrons outside shielding of one of the beam lines of the Super Hilac at Lawrence Berkeley National Laboratory. This field was quite low in both intensity and energy, but nevertheless it provided useful measurements. Another soft spectrum was that produced by SHEBA, a homogeneous critical assembly located at Los Alamos National Laboratory. We made measurements at several distances from this assembly and behind steel and concrete shields.⁶² The assembly produced a significant number of gamma rays per neutron which severely tested the pulse-shape discrimination system. Nonetheless, good spectral data were obtained.

More recently we participated in taking measurements to determine the leakage of the Little Boy Assembly at Los Alamos.⁶³ This assembly, run at the COMET facility, was a mock-up of the weapon detonated at Hiroshima and was measured to verify recent recalculations of the dose versus distance curves used to determine the doses received by the survivors; these data have considerable bearing on the understanding of the biological effects of neutrons on humans. An example of our results is shown in Fig. 58. The data

Figure 57. The neutron spectrum measured at two meters from a ^{252}Cf source enclosed in a 25-cm-thick heavy water moderator.

Figure 58. Comparison of the calculated and measured spectrum at two meters from the side (90 degrees) of the COMET assembly.

were taken at two meters at the side of the assembly, for which the angle was defined as 90 degrees. Our measurements were made with the assembly mounted in a low scatter configuration. We obtained reasonable agreement with calculations of the spectrum provided by Los Alamos. Once again our low energy results fall above the calculations indicating problems with our multiple scattering corrections.

7. CONCLUSIONS

We have developed a liquid-scintillator fast-neutron spectrometer that is well adapted to radiation protection measurements. We studied each component of the detector system and the data handling procedures associated with it, and in many cases we were able to make improvements. The resulting spectrometer has been used with good success for measurement both in the laboratory and in the field.

Many factors affect the performance of a liquid-scintillator neutron spectrometer. For example, the detectors we built include a 25-mm-long glass light pipe between the scintillator cell and the photomultiplier tube (PMT). This addition was made after measurements showed that a light pipe significantly improved resolution. In another experiment using energetic neutrons and gamma rays, we found that the circuit used to provide the operating voltages for the PMT must have a low impedance between the high voltage supply and the dynodes to ensure linear operation over the wide range of pulse heights that can be produced by a neutron spectrum. We designed a special transistorized circuit to provide the required low impedance.

We found a commercially available pulse-shape discriminator (PSD) circuit that was reasonably easy to use and worked over the energy range of interest. We discovered care had to be taken in its use, however, because input signals that exceeded that range of the internal discriminators (but that were still within the specifications) could produce spurious output signals. This problem was minimized by operating the unit in a mode that increased its dead time, often to values greater than those produced by the analog-to-digital converter (ADC) in the multichannel analyzer (MCA). Only compensation for the ADC dead time is included in the clock in the MCA. Fortunately, a dead time signal was available from the PSD, so we developed a special clock to combine

it with the ADC dead time. In order to operate the PSD at practical distances from the special clock, we had to build a line driving circuit for the dead time signal.

We have a selection of detectors varying in size, shape, and age. All the detectors use the liquid scintillator NE 213 which produces light that decays with a combination of short and long time constants. These different decay times form the basis of the scintillator's pulse-shape discrimination properties. Contamination of such a scintillator with oxygen quenches the long time components. When light is produced by the recoil protons from neutrons, a larger fraction of the total light is in the long time components than it is when the light is produced by the electrons from gamma rays. Thus it is conceivable that, as a detector ages, the light output for neutrons might be affected differently than the light output for gamma rays. Detector geometry might also be important if the light from the short and long time components undergo different amounts of self absorption. To investigate these possibilities, we performed three experiments that measured the light output as a function of neutron energy and one experiment for light output as a function of electron energy. The neutron measurements involved two independent techniques--the first using monoenergetic neutrons and the second measuring neutron time-of-flight. Our results differ from the most commonly used data; however, because our data are based on multiple experiments and several detectors, we have confidence in our results.

To reduce the neutron data, we chose a differentiation technique because it was consistent with our time and computer constraints. Such techniques can result in errors at low energies because of the distortions produced in the pulse-height data by multiple scattering of the incident neutrons in the detector. At high energies there can be edge effects if a significant number of the recoil protons leave the scintillator before they have deposited all of their energy. Approximate corrections are possible for these distortions, but completely accurate corrections depend on the spectrum measured and the methods chosen to reduce the data. We obtained correction factors for multiple scattering and edge effects from a series of Monte Carlo calculations. Since many of the spectra we measured show an excess of low energy neutrons when compared with spectra calculated for the same configurations, we probably do not as yet have an optimum correction for multiple scattering. Additional Monte Carlo calculations, using continuous input spectra, would be useful.

The presence of carbon in the scintillator produces distortions for which simple corrections cannot be made. At all energies, a distortion results from recoil protons produced by neutrons that have first scattered off carbon. Light produced by recoil carbon ions distorts the low end of the pulse-height spectrum. At high energies, carbon reacts to yield alpha particles that also result in light at low pulse heights.

More complicated data reduction techniques that fit a set of known detector response functions to the unknown spectrum can account for all of the distortions listed above. Such procedures usually require a large computer and thus are not suited for field use, and they may not result in significantly better results than those obtained with a differentiation program. Recently Klein, at the Physikalisch-Technische Bundesanstalt, Braunschweig, has reported on improved techniques for calculating the large number of response functions needed for this approach and has developed an improved data reduction program that he believes could run on a smaller computer.⁶⁴

Our light output data and multiple scattering factors were used in new programs to reduce the pulse-height calibration and neutron spectrum data. We chose a neutron data reduction procedure that rebins the pulse-height data into energy bins of uniform width before differentiating. This process has multiple advantages. First, it does not require the explicit knowledge of the first (and perhaps second) derivative of light output as a function of proton energy that is needed when the pulse-height data are differentiated directly. Second, if the same energy bins are always used, light output, efficiency corrections, and the data needed to smooth the data proportionately to detector resolution can all be calculated ahead of time and accessed by the program from files. This can significantly speed up data reduction. Third, uniform energy bins simplify combining data from the same source taken at different times or at different gains. Tests showed that this approach gave results almost identical to those from a program that differentiated the pulse-height data first.

Our programs were written in the BASIC computer language and have been implemented on several small computers. With the rapid increase in the technology of small computers, other versions of the programs in FORTRAN or PASCAL are certainly possible. Recent developments of multichannel analyzer plug-in units for small computers increase the prospects for a powerful,

compact, portable system. Such a system would further simplify the ease of data taking and reduction that this system has been designed to provide.

Completely portable, battery operated, multichannel analyzers and computers already exist that would allow the spectrometer to be truly portable. The main impediment to completely portable operation is the pulse-shape discriminator, because of the large amount of power it requires. We plan to pursue the development of a lower power PSD unit.

Even with the limitations of the present system, within its energy range it fulfills most of the radiation protection needs for neutron spectrum measurements. Neutron energies from 0.5 to 20 MeV can be measured with sufficient sensitivity to produce reasonable run times in most cases. Count rate limitations may restrict measurements at high dose rates. Resolution over the entire energy range is sufficient to provide data for calculating dosimetric values or to provide calibration data for other dosimeters. The resolution may also be sufficient for shielding measurements or verification of shielding calculations.

Cases may arise in which measurements are needed at energies below the range of the scintillator. We found that the multisphere spectrometer is well suited to radiation protection measurements at lower energies.¹³ Procedures for reducing multisphere data exist that use liquid scintillator results as input for the data reduction. The major drawback is the need for considerable computer capacity to reduce the data; however, small computers are rapidly becoming available that have sufficient memory and speed to alleviate this problem. We have recently begun to develop our program to reduce multisphere data on a small computer.

Situations may exist in which measurements need to be reduced as they are being recorded. Techniques have been reported for doing this with a liquid scintillator.⁵⁵ Variations on this procedure or on those we already use might satisfy most real-time requirements. When ease of operation is added to the requirements for energy range, sensitivity, and real-time data reduction, the system becomes capable of operation by non-spectroscopists. The ultimate goal of our work is to enable the field health physicist to make detailed evaluations of neutron fields. Considering the pace of developments in computer-operated instruments, this goal may be reached in the near future.

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