Interim Report

Neutron Dosimetry at Commercial Nuclear Plants

Annual Report of Subtask D: TEPC Feasibility

F. M. Cummings
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ABSTRACT

As part of a larger program to evaluate personnel neutron dosimetry at commercial nuclear power plants, this study was designed to observe the feasibility of the use by NRC licensees of the tissue equivalent proportional counter (TEPC) system as a neutron monitoring instrument.

Laboratory tissue equivalent proportional counters were irradiated using ^{252}Cf sources at NBS and PNL and were irradiated inside containment of four operating nuclear power plants (two boiling water reactors and two pressurized water reactors). On the average, neutron dose-equivalent rates determined using the TEPC were 1.05 times the calculated dose-equivalent rates for the bare and moderated ^{252}Cf sources and 0.86 times the dose-equivalent rates determined using the multispheres inside containment of nuclear power plants. Further, neutron dose equivalent rates determined using portable remmeters were an average of 1.71 times the dose equivalent determined using the multispheres inside the containment of nuclear power plants. It was observed that while electronic noise from temperature and vibrational effects inside containment prohibited an adequate measure of absorbed dose from gammas, the measurement of neutron absorbed dose was unaffected by these environmental parameters. It is recommended that for use inside containment at nuclear power plants 1) the laboratory scale TEPC is the superior technique for accurate determination of neutron dose equivalent, 2) for remmeters similar to the one evaluated in this study, neutron dose equivalent response should be corrected to account for dependence of response on neutron energy or the remmeters should be calibrated using a moderated neutron source, and 3) at present, the TEPC should not be used to measure absorbed dose from gammas. Upon the advent of a proven miniaturized TEPC, this instrument may prove to be a desirable replacement for current portable neutron monitoring devices for the determination of dose equivalent inside containment of commercial nuclear power plants.

SUMMARY

This study is part of a larger program to evaluate personnel neutron dosimetry at commercial nuclear power plants. Results of previous tasks in the program indicate that portable remmeters used inside containment of nuclear power plants to determine neutron dose equivalent rates respond high compared to reference values. This high response demonstrates a significant dependence of the instrument response on the energy of incident neutrons.

A laboratory tissue equivalent proportional counter system (TEPC) was used to measure absorbed neutron doses and determine neutron dose equivalents by using quality factors inferred from the absorbed dose distribution for neutron fields encountered inside containment of operating nuclear power plants. The TEPC was also used to measure absorbed neutron dose and determine neutron dose equivalents in well characterized neutron fields produced by bare and moderated ^{252}Cf sources at the National Bureau of Standards and at the Pacific Northwest Laboratory to provide a basis for evaluating this technique.

The TEPC system consists of the TEPC detector, a preamplifier, a high voltage power supply, signal and high voltage cables, a spectroscopy amplifier, an analog to digital converter (ADC), a multichannel analyzer, tape cassette for data storage, and a computer to analyze data. The electronics listed above are the same electronics used to support the multisphere measurements which were used as reference values throughout this study in order to provide continuity with the other tasks in the program. The two systems measure different quantities though; the TEPC measures absorbed dose in a simulated volume of tissue in air from charged secondary particles, while the multisphere system measures the number of thermal neutrons ($1/v$ detector) at the center of the polyethylene spheres. The TEPC measures absorbed dose directly while the multisphere technique infers kerma to element 57 by mathematically constructing the neutron flux spectrum and applying flux-to-kerma conversions. The dose equivalent is determined using the TEPC by multiplying the absorbed dose by a quality factor based on the distribution of dose events. The multisphere data is used to determine dose equivalent by using flux to dose equivalent conversion factors. The quality factors determined by the two techniques will be inherently different because the quality factor

determined using the TEPC is based on the linear energy transfer of secondary charged particles while the quality factor determined using the multisphere technique is the mathematical maximum value in a 15-in. sphere for neutrons in particular energy groups.

The inherent differences between the TEPC and portable remmeters lie chiefly in two areas. The first difference is the dependence of the particular measurement technique on the energy of incident neutrons. Portable remmeters have demonstrated energy dependence (Schwartz et al. 1983; Hankins 1977; Cosack and Lesiecki 1981) such that the response of the remmeter must be related to dose equivalent rate through appropriate calibration or correction techniques. The TEPC directly measures absorbed dose to an equivalent volume of tissue in air and determines a quality factor pertinent to each neutron radiation field from the LET distribution and as such needs no external calibration.

Pertaining to the portability of the two techniques, currently, the remmeter is much more portable (20-25 pounds) than the TEPC and associated electronics (approximately 80 pounds). Additionally, the laboratory TEPC does not provide a read out at the time of measurement.

This study demonstrates that the TEPC technique is conceptually superior to the portable remmeter for determining dose equivalent. A miniaturized self-contained TEPC instrument will be evaluated later to prove over all superiority.

The TEPC measurement technique in this task differs from the technique used in Subtask B to evaluate the responses of personnel neutron dosimeters. The difference lies in the selection of TEPC systems using low-noise preamplifiers and a system of two amplifiers per measurement. Using two amplifiers per measurement permitted analysis of events over the range of roughly 0.3 keV/micrometer to 1000 keV/micrometer. Routine TEPC measurements employing a single amplifier do not have the dynamic range to accommodate this depth of analysis. The U.S. Department of Energy has under taken the development of a portable TEPC-based instrument which will determine neutron- and gamma-dose equivalent/rates in mixed radiation fields.

Because the TEPC measures neutron absorbed dose directly, is more straightforward in analysis than the multisphere technique and because the energy dependence of remmeters leads to an over estimation of neutron dose-equivalent rates in containment by a factor of 1.71 on the average, the authors concluded that 1) the TEPC is the superior technique for accurate determination of neutron dose-equivalent/rate inside containment of nuclear power plants; 2) that results from remmeters currently in use and similar to the one evaluated herein be adjusted to account for energy dependence or that the remmeters be calibrated using a moderated neutron source which provides response similar to the response to neutrons found inside containment of commercial nuclear power plants, and 3) that the TEPC not be used to measure absorbed dose from photons at this time. Further, when a miniaturized portable version of the TEPC is available, it should be evaluated as to its application to dose equivalent determination inside containment of commercial nuclear power plants thereby verifying the appropriateness or inappropriateness of the technique for routine neutron dose equivalent monitoring.

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INTRODUCTION

This study is part of a six year project, funded by the U.S. Nuclear Regulatory Commission (NRC), to evaluate personnel neutron dosimetry at commercial nuclear power plants. In the first two phases of the project, neutron spectrum, flux, and dose measurements indicated that 1) the average energy of neutrons producing the significant amounts of dose inside containment of pressurized water reactors was on the order of 50 keV and 2) the only commercially available dosimeter appropriate for use in those fields was the TLD-albedo which incorporated ^6Li . The predominance of neutrons with energies less than 100 keV caused the dosimeters to indicate that more dose equivalent was received than actually was received. The reasons for that 'high response' lie in the energy dependence of the response of the TLD and in the choice of calibration sources (Endres et al. 1981; Cummings et al. 1983).

While noting the energy dependence of the TLD, a similar dependence (though not as severe) was noted in the portable neutron monitoring instruments, called remmeters. Depending on the type of remmeter chosen, these instruments responded 1.5 to 8 times higher than the reference measurements (multispheres and tissue equivalent proportional counters [TEPC]). Because the TEPC measures absorbed dose directly and is self-calibrating, it was evaluated for its application to neutron dose measurements inside containment of commercial nuclear power plants and also for its application in photon dose measurements. The question to be answered was: could the TEPC be used to accurately measure absorbed dose from neutrons and gammas and then be used to determine dose equivalent using quality factors inferred from the distribution of dose events? In addition, the TEPC technique needed evaluation to demonstrate the feasibility that a TEPC-based system could adequately serve as a routine neutron monitoring instrument.

To answer the questions, a laboratory TEPC was irradiated using bare and moderated ^{252}Cf sources at the National Bureau of Standards (NBS) and at the calibration facility at Pacific Northwest Laboratory (PNL) and measurements were performed inside containment of operating commercial nuclear power plants. While the TEPC accurately measured absorbed dose from neutrons and accurately determined neutron dose equivalent, the smaller events due to

photon interactions were masked by the electronic noise of the laboratory system. The average dose equivalent response of the TEPC compared to calculated neutron dose equivalents for the ^{252}Cf irradiations was 1.05 ± 0.14 . The calculated neutron dose equivalents are enumerated by McDonald et al. (1983) and by Stoddard and Hootman (1971). The average dose equivalent response of the TEPC compared to dose equivalents determined from multisphere measurements inside containment was 0.86 ± 0.20 . The multisphere system has been the reference measurement technique throughout this study and previous tasks in this program. The average dose equivalent response of remmeter compared to multisphere measurements inside containment was 1.71 ± 0.74 . The average dose equivalent response of the remmeter compared to the dose equivalent determined using the TEPC was 1.99 ± 0.78 .

The photon measurements performed inside containment with the TEPC did not yield useful results because of increased noise from the linear amplifiers and external power supplies needed for supporting the TEPC measurements. Those problems could be resolved by incorporating an internal power supply (long-life battery). Indeed, a 2-1/4-in. TEPC incorporating a low-noise preamp and internal high-voltage power supply was used to determine the neutron dose equivalent in the field produced by a O_2O -moderated ^{252}Cf source at PNL. Even though the conditions were tightly controlled, enough electronic noise was introduced by the long signal cables and linear amplifiers to only allow analysis to the 0.5 keV/micrometer range. In conclusion, the present TEPC systems are incapable of resolving the very low-energy recoil electrons produced by photons from those produced by electronic noise.

This project will continue into FY-1984 in order to evaluate a portable version of the TEPC with a built-in microprocessor for determination of neutron absorbed dose and dose equivalent (and the associated rates) at the time of measurement. The feasibility of using this portable TEPC for routine monitoring at licensee facilities will be investigated.

INSTRUMENT DESCRIPTIONS

The TEPC system used in this task (Figure 1) consists of the TEPC detector, a preamplifier, a high voltage power supply, signal and high voltage cables, a spectroscopy amplifier, an analog to digital converter (ADC), a multichannel analyzer (MCA), tape cassette read out, and a personal computer to analyze data. The TEPC detector is a hollow sphere with walls that are 0.123 in. thick and constructed from Shonka A-150 plastic. A single wire anode has been stretched between the two poles of the sphere. The detector is filled with propane-based filling gas before each set of measurements. Interactions between neutrons and the atoms in the plastic detector wall give rise to recoiling ions which traverse the cavity (see Figure 2). The energy deposited in the gas by the recoiling ion is equal to the product of the linear energy transfer and the length of the path traversed by the ion. Further description of the TEPC is presented in the following three sections: 1) the meaning of "tissue equivalence," 2) the production of signal, and 3) the determination of quality factor and dose equivalent.

The multisphere system (Figure 3) consists of a $^6\text{LiI}(\text{Eu})$ detector, preamplifier, high voltage power supply, signal and high voltage cables, a spectroscopy amplifier, an ADC, MCA, tape cassette read out, and a main frame computer to analyze data. A measurement consists of determining the net count rate due to the $^6\text{Li}(n,\alpha)^3\text{H}$ reaction from the bare detector, from the detector covered with a cadmium shield and from the detector at the center of each of five polyethylene spheres of the following diameters: 3, 5, 8, 10, and 12 inches. The net count rates are used in an iterative unfolding code to solve the Fredholm integral for neutron energy spectrum and flux (Endres et al. 1981).

The various aspects of the TEPC technique are further described below and the reader is directed to Endres et al. (1981) for a discussion of the multisphere technique.

TISSUE EQUIVALENCE

The tissue equivalent proportional counter (TEPC) is the only instrument currently available which can be used to measure absorbed dose from neutrons

FIGURE 1. TEPC System

FIGURE 2. Tissue Equivalent Proportional Counter Construction

FIGURE 3. Multisphere System

and infer a quality factor based on the way the dose is deposited in the counter (absorbed dose distribution).

The tissue equivalence (TE) of the counter is an important consideration in that the measurement is used to infer how energy is deposited in tissue from neutron induced events. The concept of tissue equivalence for the counter means that one expects neutrons (the radiation of interest in this case) to interact in the counter much the same way that the neutrons interact in tissue. For this condition to be true, the interaction cross sections of atoms comprising tissue and the plastic used in the counter have to be considered.

The 0.123-in. thick plastic wall of detector, Figure 2, is made of Shonka A-150 plastic. The composition of the plastic is enumerated in ICRU Report 26 (ICRU 1977) and is summarized in Table 1.

The tissue equivalence is apparent in the percent composition regarding hydrogen and nitrogen relative to ICRU muscle tissue. The importance of the equality of hydrogen and nitrogen and the relative unimportance of amounts of carbon and oxygen lies in the amount of dose deposited in tissue from neutron interactions with those various elements. The energy transfer from neutrons

TABLE 1. Elemental Composition of TE Plastic (ICRU 1977)

Element	Percent Weight		
	ICRU Muscle Tissue	A-150 Design Composition	A-150 Chemical Analysis (std. dev. (a))
Hydrogen	10.2	10.1	10.3 (0.1)
Nitrogen	3.5	3.5	3.5 (0.07)
Oxygen	72.9	5.2	6.4 (0.6)
Carbon	12.3	77.6	77.1 (0.3)
Calcium	0.007	1.8	NA ^(c)
Fluorine	-	1.7	NA ^(c)
Total	98.8 ^(b)	99.9	97.3

(a) Standard deviation of 5 replicate samples analyzed.

(b) The 1.1 percent remainder consists of Na, Mg, P, S, and K.

(c) NA: no analysis.

to tissue is illustrated in Figure 4 (ICRU 1969). For neutrons with energy below 10 MeV, the predominant modes of energy transfer involve mainly nitrogen and/or hydrogen. Further, if one consults tabulated values of first collision dose to standard tissue, TE plastic and TE gas for neutrons with energies between 0.01 and 10 MeV, the maximum difference in total kerma is 5% (NBS 1961). It is for these reasons that the TEPC exhibits tissue equivalence.

Table 2 contains the composition of ICRU tissue and TE gas and forms the basis for the same arguments as for the plastic.

Tissue equivalence for photon interactions is a valid concept only for photons with energies greater than 0.1 MeV, Figure 5. It can be noted that below 0.1 MeV the tissue equivalence is no longer valid. This is because the primary interaction of photons with energies less than 0.1 MeV is the photo-electric interaction. Since the cross section for photon absorption increases with the fourth power of the atomic number of the absorbing medium and with the inverse cube of the energy of the photon (Evans 1968) and since the TE plastic contains no trace quantities of the heavier elements (Tables 1 and 2) then the first collision dose in the TE plastic does not simulate the first collision dose in tissue for photons below 0.1 MeV.

FIGURE 4. Kerma/Fluence (product of the mass energy transfer coefficient and the neutron energy) for Hydrogen, Carbon, Nitrogen, Oxygen, and Wet Tissue (ICRU 1969)

TABLE 2. Elemental Composition of TE Gas (ICRU 1977)

Element	ICRU Muscle Tissue	Percent Weight	
		TE Gas Methane-Base (a)	TE Gas Propane-Base (b)
Hydrogen	10.0	10.2	10.3
Nitrogen	3.5	3.5	3.5
Oxygen	71.6	40.7	29.3
Carbon	14.9	45.6	56.9
Total	100.0	100.0	100.0

(a) 64.4% methane, 32.4% carbon dioxide, 3.2% nitrogen (partial pressures); Rossi and Failla 1956.

(b) 55.0% propane, 39.6% carbon dioxide, 5.4% nitrogen (partial pressures); Srdoc 1970.

FIGURE 5. First Collision Dose Versus Photon Energy (NBS 1961)

The application of the TEPC with respect to neutrons and photons must be considered from the perspective of the irradiations encountered and their effects upon dose deposition mechanisms. Inside containment of pressurized water reactors (PWR), the predominant numbers of neutrons are below 1.0 MeV in energy (Endres 1981) and the predominant numbers of photons are emitted from ^{60}Co (1.17 and 1.33 MeV) and ^{137}Cs (0.66 MeV). Hence the characteristic tissue equivalence for the TEPC holds for both neutrons and photons generally. In boiling water reactors the added problem of ^{16}N (emitting photons between 6 and 7 MeV) is encountered. In this region the pair production cross section increases roughly as the square of the atomic number (Evans 1955) so the tissue equivalence may not hold for the photon contribution. The tissue equivalence may not hold in those plants in which there are large numbers of low-energy photons (<0.1 MeV) due to the presence of noble gas and iodine.

Overall the TEPC will provide a close measure of the absorbed dose to tissue if events between 0.1 keV/micrometer and up are used for analysis.

SIGNAL PRODUCTION

Gas Gain

Ionization is the only mode of energy transfer from radiation to matter that will be considered in this discussion. The way that neutrons and gamma rays transfer energy to the TEPC is by interacting with the counter wall and producing secondary charged particles which traverse the gas cavity.

In optimizing a proportional counter, it is desirable to get the maximum gain, or gas amplification, in order to finely discriminate voltage pulses, produced by the passage of the secondary particles. The gain may be manipulated by choosing the appropriate filling gas or by electronic amplification of the signals, or both. In considering the type of TE counting gas to be used, two types are available which produce the best results: methane (CH_4) based TE gas and propane (C_3H_8) based TE gas. The relationship of gain to gas characteristics is given by:

$$\ln M = \frac{A}{\Delta V} \left[\ln \frac{B}{Kp} \right] \quad (\text{from Knoll 1979}) \quad (1)$$

where M = gas multiplication, or gain
 ΔV = potential difference through which an electron moves between successive ionizing events
 p = gas pressure
 K = minimum value below which multiplication cannot occur
 $A = \ln 2 \cdot V / \ln (b+a) = \text{constant}$
 V = applied voltage across the counter
 a = radius of anode
 b = radius of counter
 $B = V / [a \cdot \ln (b+a)]$.

The only values in equation 1 which are characteristic of the particular counting gas will be the ΔV , K , and p . Values for ΔV and K are given in Table 3 for pure methane and propane as an illustration to show how they differ.

The pressure of the gases will be a function of the density as certain numbers of hydrogen atoms are necessary to arrive at an equivalent site size of tissue. Table 4 gives the densities of the gases and pressures used to achieve a 1 micrometer equivalent site size.

It can be seen then that the gain is a complex function of the gas and is affected by operating parameters such as pressure and applied voltage as well as gas characteristics such as ΔV and K . The above discussion was developed to show why differences exist between gases. In the laboratory situation, we merely irradiated a TE-methane filled counter using a bare ^{252}Cf source, refilled the counter with TE-propane gas and reirradiated. Reference pulses were noted to be such that the propane based gas exhibited a gain that was twice that of the methane based gas.

TABLE 3. Characteristics of Counting Gases
(Knoll 1979)

<u>Gas</u> <u>(100%)</u>	<u>$K \times 10^{-4}$</u> <u>(V/cm-atm)</u>	<u>ΔV</u> <u>(eV)</u>
Methane	6.9	36.5
Propane	10.0	29.5

TABLE 4. Gas Density and Pressure for a 1 Micrometer Equivalent Site Size at 25°C

Gas	Density (g/cm ³)	Pressure	
		2-1/4-in. Counter (torr)	5-in. Counter (torr)
TE-methane	0.001136	12.9	5.8
TE-propane	0.00182	7.8	3.5

Pulse Production and Dose

Having discussed which properties of the counting system amplify the pulses, a discussion of how signals are produced and what they mean is in order. As the secondary particles (i.e., proton, heavy ion or electrons) traverse the gas cavity, they ionize gas atoms producing free electrons. These free electrons are accelerated toward the anode ionizing more atoms as they go producing an "avalanche" of electronics. The size of the avalanche is a function of the gas multiplication. As the electrons are collected at the anode, a voltage pulse is produced. The pulse is proportional to the amount of energy deposited in the gas by the passage of the secondary charged particle. If the system is calibrated then, the energy deposited in the gas can be determined for each of the events and since the mass of the gas is known, the dose can be determined. Simply, the dose is the energy divided by the mass or

$$D = \frac{k\Sigma E}{m} \quad (2)$$

where k is a proportionality constant
 ΣE is the sum of deposited energy from all the events
 m is the mass of the gas.

The absorbed dose from the passage of the charged particles and hence from the incident radiations is thus measured directly and is a close simulation of dose in tissue.

Pulse Size and Lineal Energy

As stated earlier, the size of the pulse is proportional to the energy deposited in the gas. In order to determine a quality factor and convert

absorbed dose to dose equivalent, the lineal energy spectrum must be determined (a discussion of LET, lineal energy and quality factor follows in the next section). To do this, individual pulses are recorded, after amplification, in a multichannel analyzer for subsequent analysis. In order to convert pulses to event size for quality factor determination, several assumptions are made. For instance, one such assumption is that secondary particles do not lose significant amounts of energy in traversing the cavity and travel in a straight line. The error in incorrectly analyzing heavy ions which start or stop in the gas is small for radiation protection purposes (Rossi 1968).

The reader is directed to detailed discussions of these concepts (Rossi 1968, ICRU 1977, Kellerer 1970). Suffice it to say that the assumptions lead to small errors in dose and somewhat larger errors in dose equivalent. Errors from Poisson treatment of individual events will be noted within the report.

QUALITY FACTOR AND DOSE EQUIVALENT

In 1963, the Relative Biological Effectiveness (RBE) Committee recommended to the ICRP and ICRU a means by which doses of radiation of different quality might be added. In order to avert the confusion between the RBE concept used in radiobiology and the LET dependent factor for dose activity, the ICRU (1963) coined the term quality factor and defined it as follows:

"[The ICRU] now recommends that the term RBE be used in radiobiology only and that another name be used for the linear-energy-transfer-dependent factor by which absorbed doses are to be multiplied to obtain, for purposes of radiation protection, a quantity that expresses, on a common scale for all ionizing radiations, the irradiation incurred by exposed persons. The name recommended for this factor is the quality factor (QF)."

The values of quality factor are based on average linear energy transfer ($\overline{\text{LET}}$) (RBE 1963). The $\overline{\text{LET}}$ is equal to the "stopping power" in water for the charged particles. Based on the RBE Committee recommendations, ICRP and ICRU adopted quality factor determinations that were based on $\overline{\text{LET}}$ as recommended by the RBE Committee. Those values are found in Table 5 (RBE 1963,

TABLE 5. LET-QF Relationship (RBE 1963)

<u>LET</u> <u>(keV/μ in ∞ water)</u>	<u>QF</u>
3.5 or less	1
3.5-7.0	1-2
7.0-23	2-5
23-53	5-10
53-175	10-20

ICRU 1969, ICRP 1973). The dose equivalent is then the product of the absorbed dose and the quality factor and any other pertinent modifying factors (ICRU 1976).

Unfortunately, the difficulties associated with the observation of LET distributions (i.e., statistical spread of energy loss; track diameter and curvature) make LET impossible to measure directly (ICRU 1969). Because of these limitations, Rossi defined the quantity, Y (event size), the analog of $\overline{LET}$, and showed its relationship to $\overline{LET}$ (Rossi 1968). Beyond that, Kellerer derived a relationship between y_D , the average lineal energy in the dose distribution, and L_D , the dose mean of LET distribution (Kellerer 1970). The point of all this work was to use an observable quantity to determine a quantity which is impossible to measure. The definitions below provide the insight necessary for purposes of this study, however, the reader is directed to the literature for more detailed description of these quantities.

The linear energy transfer is given by:

$$L = \frac{dE}{dl} \quad (\text{ICRU 1969}) \quad (3)$$

where L = linear energy transfer of a charged particle in a medium,
keV/micrometer
 dE = average energy locally imparted to the medium by the passage of
a charged particle of specified energy
 dl = distance traversed by the charged particle across the volume
of interest.

The event size is given by:

$$Y = \frac{E}{d} \quad (\text{Rossi 1968}) \quad (4)$$

where Y = event size, keV/micrometer
 E = energy deposited in medium by the passage of a charged particle
 d = diameter of the spherical volume of interest.

The lineal energy is given by:

$$y = \frac{E}{\bar{T}} \quad (5)$$

where y = lineal energy, keV/micrometer
 E = energy deposited by the passage of a charged particle
 $\bar{T}$ = mean chord length of the spherical volume of interest.

The dose distribution is proportional to the product of the lineal energy and the number of events of the given lineal energy, or:

$$D(y) \propto y * N(y)^{(a)} \quad (6)$$

where $D(y)$ = dose deposited as a result of lineal energy, y , rad
 y = lineal energy, keV/micrometer
 $N(y)$ = number of lineal energy events of size, y

The dose weighted mean lineal energy, or average lineal energy is given by:

$$\bar{y}_D = \frac{\int_{y_1}^{y_2} y D(y) dy}{\int_{y_1}^{y_2} D(y) dy} \approx \frac{\sum_{y_1}^{y_2} y D(y)}{\sum_{y_1}^{y_2} D(y)} \quad (7)$$

(a) Note: For an exact treatment, see Rossi 1968.

where $\bar{y}_D$ = average lineal energy in the dose distribution between lineal energy events y_1 and y_2

y , $D(y)$ are defined previously.

The dose weighted mean lineal energy is related to the dose weighted mean linear energy transfer by:

$$\bar{y}_D = \frac{3}{2} \cdot \frac{\delta_2}{d} + \frac{9}{8} \cdot \bar{L}_D \quad (\text{Kellerer 1970}) \quad (8)$$

where $\bar{y}_D$ = average lineal energy in the dose distribution where
 $y_D(y)$ = density deposited divided by the mean chord length
 (equation 7)

$3/2 \cdot \delta_2/d$ = energy straggling term (neglected for our measurements)

$\bar{L}_D$ = dose mean LET.

Quality factor can be related to linear energy transfer by fitting the published data to the following equation:

$$Q = A + B \ln(\bar{L}_D) + C \ln(\bar{L}_D)^2 + D \ln(\bar{L}_D)^3 + E \ln(\bar{L}_D)^4 \quad (a) \quad (9)$$

where Q = quality factor

$\bar{L}_D$ = dose mean LET (from equation 8)

and finally, the dose equivalent may be determined by

$$H = Q \cdot \int_{y_1}^{y_2} D(y) dy \approx Q \sum_{y_1}^{y_2} D(y) \text{ or } \sum_{y_1}^{y_2} Q(y) \cdot D(y) \quad (10)$$

(a) Note: This is an analytical fit to figure 2 in ICRP 21 (ICRP 1973). Other approximations have been recommended as well, but it was just as easy to employ this formula since the data reduction was performed by computer.

where H = dose equivalent, rem
 Q = average quality factor from experimental quantities,
(see equations 5 through 9)
 $\Sigma D(y)$ = dose from events between y_1 , and y_2 .

Equation 10 finally gets to the point. The quality factor is inferred from an average LET which has been approximated using the event size spectrum, measured using the TEPC. The absorbed dose is measured directly using the TEPC and therefore an approximate dose equivalent is determined using measurable quantities.

DATA ANALYSIS

COMPUTER CODE

As was mentioned earlier, pulses produced by the charged secondary particles are amplified by an electronic preamplifier and a linear amplifier and stored in a multichannel analyzer. The data (counts per channel) are usually transferred to cassette tape and later, to computer disk file. A description of the data analysis follows and a brief flow chart is given in Figure 6.

The data at this point reside on a 5-in. floppy disk in the form of three parameters: (1) the number of channels (e.g., 2048), (2) measurement title, and (3) a serial array in which is contained the number of counts in each channel.

When analyzing data, the operator is queried about certain operating parameters (i.e., the counter diameter, gas filling pressure and temperature at time of gas fill). These parameters are used in equation (11) to determine the mass of the gas.

$$D = 1.602 \times 10^{-8} \sum_{h1}^{h2} C \cdot h \cdot N(h) \cdot (V)^{-1} \cdot (\rho)^{-1} \quad (\text{ICRU 1977}) \quad (11)$$

where D = absorbed dose, rad
 C = channel to energy calibration, MeV/micrometer
 h = channel number
 N(h) = counts in channel h
 h1 = starting data channel
 h2 = ending data channel
 V = gas volume, cubic centimeters
 ρ = gas density, g/cubic centimeter

The counter diameter is used to determine the volume of the counter while the pressure and temperature are used to correct the density. Volume times density equals the mass of gas in the counter, or

$$M(g) = \rho(g/cc) \cdot V(cc) \quad (12)$$

FIGURE 6. TEPC Analysis Flow Chart

The constant 1.602×10^{-8} , energy calibration, C , and the mass are included in the proportionality constant which makes equation (6) an equality instead of just a proportionality.

The proton drop point, P-drop, corresponds to the maximum LET, or stopping power, exhibited by a recoil proton which traverses the diameter of the cavity. More specifically, the stopping power in the gas is at a maximum for protons at ~ 100 keV/micrometer (Glass and Samsky 1967). The technique used to determine the point drop point involves locating the point in the dose distribution $[h \cdot N(h)]$ where the second derivative goes through a minimum just below the heavy ion recoil region, known as the point of inflection. The individual values in the dose distribution are digitally filtered for smoothness using a 15 point smoothing function. The point of inflection, identified in Figure 7, corresponds to the point where the slope of the curve changes direction. The proton drop point times the site equivalent diameter corresponds to the "c" in equation (11) and has units of keV/channel.

The importance of the determination of proton drop point cannot be overstated. On the one hand it provides an self calibration point for the TEPC that is independent of the energy of the incident neutron and hence, the calibration source. (A beam of alpha particles from a ^{244}Cm source internally fixed in the counter provides a reference to the proton drop point.) On the other hand, the proton drop point may shift over time due to gain shifts in

FIGURE 7. Raw Data Spectrum from a Reactor Measurement Using the TEPC

the counting system (most noticeably from temperature effects in electronic components) and one may not be able to determine a sharply defined P-drop. Also, statistical variations in the count distributions of low dose measurements may lead to incorrect P-drops. Generally, the determination of the P-drop is stable and accurate enough for personnel dosimetry purposes. For example, if a small integral absorbed dose is measured (i.e., <10 mrad) the deviation in measurement statistics (30-40%) would greatly overshadow the effect of misplacing the proton drop point by a few percent (absorbed dose is proportional to the location of the proton drop point through the conversion of channel to pulse height).

The discrimination of events due to electrons traversing the cavity from events due to protons traversing the cavity at small lineal energies (~ 10 keV/ μ) is difficult. Typically the techniques include: (1) the subtraction of a previously stored spectrum of events due to photon interactions in the counter wall; (2) the determination of the minimum between the two regions in the y-squared distribution (the y-squared distribution is the distribution of $y \cdot D(y)$ or $y \cdot y \cdot N(y)$ (Figure 8) and assumption that events which are to the left of that point (less energetic) are due to photon interactions and events to the right of that point (more energetic) are due to neutrons; (3) finding the respective slopes of the curves (in the y-squared distribution) on either side of the minimum and calculate doses by extrapolation of those curves; and (4) setting a default value (e.g. 7 keV/micrometer from ^{252}Cf irradiation) above which events are assumed to be due to neutron interactions and below which events are assumed to be due to photon interactions. The development of techniques 1 and 3 were sufficiently complex to be outside the scope of this study, so only techniques 2 and 4 were used subject to the following criteria. If the second technique is not feasible due to too little data, or not enough spread (e.g., proton drop point too low) then the fourth technique will be employed during this study. Additionally, an attempt will be made to present and discuss the photon induced events and doses.

FIGURE-6. Neutron and Gamma Dose Measured by the Tissue Equivalent Proportional Counter

The calculation of neutron absorbed dose is straightforward and is performed using equation (1). Two methods were used to determine a quality factor from the dose spectra, the Kellerer approximation and the Borak approximation. The Kellerer approximation involved finding the average event size/linear energy transfer as enumerated in equations (7) through (9) and applying a fourth order polynomial of the log of average linear energy transfer. The Borak approximation determined dose equivalent by applying the same equation to each event size and integrating the individual products of quality factor, event size, and number of events of the particular size, equation (11) (Borak and Stinchcomb 1982).

RESULTS

NBS - ^{252}Cf IRRADIATIONS

Two sources were used at the NBS to irradiate the TEPC: NS-79 in the bare ^{252}Cf configuration and NS-86 in the D_2O -moderated ^{252}Cf configuration. The TEPC was placed at 81.4 cm from the source for the bare ^{252}Cf irradiation and at 56.4 cm from the source for the moderated ^{252}Cf irradiation. The data are summarized in Table 6.

The TEPC used at NBS for these measurements was a 5-in. diameter spherical counter (#502) manufactured by Far West Technologies (FWT). The signal was amplified using an Ortec preamp (142-PC) and amplifier (Ortec 572). Data were collected and stored in a Canberra-Series 40[®] multichannel analyzer and subsequently written to cassette tape (see Figure 1).

TABLE 6. Neutron Dose Measurements on Bare and Moderated ^{252}Cf at NBS

	Source Configuration	Absorbed Dose Rate (mrad/hr)	Quality Factor		TEPC DE Rate (mrem/hr)	Delivered DE Rate (mrem/hr)	Ratio TEPC/Delivered
			Kellerer	Borak			
Gamma	Bare	22.1 ± 2.76 ^(a)	1.0	1.2	22-26	42 ^(b)	0.53-0.62
Neutron	Bare	59.4 ± 3.48	8.8	10.0	523-594	595 ^(c)	0.88-1.00
Gamma	D ₂ O-moderated	45.6 ± 3.97	1.0	1.4	46-64	116 ^(d)	0.40-0.55
Neutron	D ₂ O-moderated	61.1 ± 3.60	9.2	10.4	562-611	645 ^(c)	0.87-0.95

(a) One standard deviation from Poisson statistics.

(b) From Stoddard and Hootman 1971.

(c) Supplied by NBS.

(d) From McDonald et al. 1983.

PNL - ^{252}Cf IRRADIATIONS

PNL possesses a 15-cm D_2O -moderated ^{252}Cf source in a low-scatter irradiation facility. The D_2O is contained in a 0.8-mm thick stainless steel shell surrounded with a 0.5-mm thick cadmium shell. The design and construction of the source is similar enough to the source described by Schwartz and Eisenhauer (1980) that the reader is directed to that document for further detail.

The moderated ^{252}Cf source was used at the PNL-Calibration Facility to irradiate the TEPC in order to compare to the NBS measurements. The TEPC which was used was an optimized low-noise, self-contained, 2-1/4-inch diameter, spherical TEPC manufactured by EG&G, Santa Barbara in conjunction with Far West Technologies. The TEPC was placed at 1 meter from the source for all irradiations. The data are summarized in Table 7.

TABLE 7. Neutron Dose Measurements on Moderated ^{252}Cf at PNL

	Source Configuration	Absorbed Dose Rate (mrad/hr)	Quality Factor		TEPC DE Rate (mrem/hr)	Delivered DE Rate (mrem/hr)	Ratio TEPC/Delivered
			Kellerer	Borak			
Gamma	Bare	$0.89 \pm 0.07^{(a)}$	1.0	1.2	1	3 ^(b)	0.33
Neutron	Bare	4.4 ± 0.2	8.1	9.8	36-43	43 ^(c)	0.84 - 1.00
Gamma	D ₂ O-moderated	23.9 ± 1.2	1.0	1.2	24-29	31 ^(b)	0.77 - 0.94
Neutron	D ₂ O-moderated	22.1 ± 0.47	8.0	9.7	177-214	170 ^(d)	1.0 - 1.3

(a) From Poisson statistics.

(b) From Stoddard and Hootman 1971.

(c) Supplied by PNL.

(d) From McDonald et al. 1983.

REACTOR IRRADIATIONS

TEPC measurements were performed at six commercial nuclear power plants during this study, including four PWRs and two BWRs. Data are presented for measurements at four of the plants (two PWRs and two BWRs) as electronic difficulties during one measurement trip interfered with the collection of the TEPC data. The irradiations were performed inside containment of the PWRs and inside the dry wells of the BWRs at various power levels. The low-noise counters which contained high voltage power supplies and preamps and which were specially ordered from EG&G, Santa Barbara, for this program failed inside some of the plants because of the high temperatures and vibrations encountered. All the TEPC measurements were performed with the same (5-in. diameter) counter (#502) except those at reactor 4. The TEPC measurements at reactor 4 were performed using a 5-in. diameter self-contained TEPC #185. Where possible, multisphere runs and remmeter measurements were performed for comparison.

Reactor 1

Reactor 1 is a boiling water reactor. The measurements were performed at 60% power inside the dry well. The locations constituted various levels above the entry hatch and represented areas workers could be expected to enter. The last measurement (#4) was performed in the personnel hatch in conjunction with a multisphere measurement. High temperatures, time, and high dose rates prohibited taking high gain measurements at this reactor, so data are presented for neutrons only (Table 8). Additional data regarding average energy, average LET, etc. are presented in the appendix.

TABLE 8. Neutron Dose Measurements for Reactor 1 (BWR)

Location	Absorbed Dose Rate (mrad/hr)	Quality Factor		TEPC DE Rate (mrem/hr)	Reference DE Rate (mrem/hr)	Ratio TEPC-Reference	SNOOPY (mrem/hr)
		Kellerer	Borak				
1	13.2 ± 1.1 ^(a)	8.7	10.9	115-144	-	-	300
2	6.48 ± 0.6	8.4	10.6	54-69	-	-	150-180
3	137 ± 27	9.1	10.8	1240-1480	-	-	2500
4	12.8 ± 1.5	8.5	10.6	109-136	-	-	330
5	5.53 ± 0.5	8.8	11.2	49-62	49 ^(b)	1-1.27	100

(a) One standard deviation from Poisson statistics.

(b) Multisphere measurement.

Reactor 2

Reactor 2 was also a BWR. Measurements were performed at 10% power in several locations. High gain measurements were performed enabling analysis of low LET events (below 5 keV/micrometer). The data are presented in Table 9.

TABLE 9. Neutron Dose Measurements for Reactor 2 (BWR)

Location		Absorbed Dose Rate (mrad/hr)	Quality Factor		TEPC DE Rate (mrem/hr)	Reference DE Rate (mrem/hr)	Ratio TEPC/Reference	SNOOPY (mrem/hr)
			Kellerer	Borak				
1	Gamma	232 ± 31 ^(a)	1.0	1.3	232-305	470 ^(b)	0.49-0.65	450
	Neutron	36.5 ± 2.4	10.1	11.9	369-436	450 ^(c)	0.82-0.97	
2	Gamma	70.7 ± 8.2	1.0	1.4	71-101	470 ^(b)	0.15-0.21	450
	Neutron	41.5 ± 3.2	10.9	12.3	450-511	450 ^(c)	1.0-1.14	
3	Gamma	113 ± 29	1.0	1.2	113-132	-	-	
	Neutron	1.81 ± 0.15	9.5	11.7	17-21	-	-	
4	Gamma	201 ± 50	1.0	1.1	201-226	-	-	
	Neutron	4.49 ± 0.4	9.8	11.7	44-53	-	-	

(a) One standard deviation from Poisson statistics.

(b) Portable ion chamber.

(c) Multisphere measurement.

Reactor 3

Reactor 3 is a pressurized water reactor. The two TEPC measurements presented below were performed at 50% power with corresponding multisphere measurements. The data are summarized in Table 10. Single-gain measurements were performed and while data were insufficient to render an accurate gamma measurement, the gamma data are still presented for comparison purposes.

TABLE 10. Neutron Dose Measurements for Reactor 3 (PWR)

Location		Absorbed Dose Rate (mrad/hr)	Quality Factor		TEPC DE Rate (mrem/hr)	Reference DE Rate (mrem/hr)	Ratio TEPC/Reference	SNOOPY (mrem/hr)
			Kellerer	Borak				
1	Gamma	1.0 ± 0.3	1.2	1.7	12-17	12 ^(a)	1.00-1.42	
	Neutron	2.6 ± 0.2	9.9	11.3	26-29	35 ^(b)	0.74-0.83	55
2	Gamma	1.4 ± 0.3 ^(a)	1.9	2.5	28-36	50 ^(b)	0.56-0.72	
	Neutron	5.6 ± 0.4	9.7	11.9	54-66	93 ^(c)	0.64-0.79	80

(a) One standard deviation from Poisson statistics.

(b) Portable ion chamber measurement.

(c) Multisphere measurement.

Reactor 4

Reactor 4 is a pressurized water reactor. The five TEPC measurements were performed in conjunction with the multisphere measurements at 100% power. Single gain measurements were performed, so the gamma portions of the data below 1 keV/micrometer are masked by electronic noise. The data are summarized in Table 11.

TABLE 11. Dose Measurements for Reactor 4 (PWR)

Location		Absorbed Dose Rate (mrad/hr)	Quality Factor		TEPC DE Rate (mrem/hr)	Reference DE Rate (mrem/hr)	Ratio TEPC/Reference	SNOOPY (mrem/hr)
			Kellerer	Borak				
1	Gamma	3.0 ± 1.4	1.0	1.4	3-4	-	-	-
	Neutron	0.9 ± 0.1	8.4	10.5	8-10	17	0.47-0.59	27
2	Gamma	3.7 ± 1.1	1.8	2.3	6-8	-	-	-
	Neutron	0.9 ± 0.1	8.5	10.8	8-10	12	0.67-0.83	15
3	Gamma	8.3 ± 4.2	1.0	1.2	8-10	-	-	-
	Neutron	1.3 ± 0.1	8.2	10.3	11-13	16	0.69-0.81	33
4	Gamma	10.8 ± 4.2	1.3	1.8	11-15	-	-	-
	Neutron	3.0 ± 0.2	9.6	11.7	29-35	35	0.83-1.00	68
5	Gamma	2.6 ± 0.7	1.3	1.8	3-4	-	-	-
	Neutron	1.3 ± 0.1	8.7	10.8	12-14	16	0.75-0.88	53

DISCUSSION OF RESULTS

The results of these measurements lead to several conclusions regarding dose measurements employing the TEPC. The results and conclusions will be discussed from the perspectives of 1) neutron measurements and 2) gamma measurements.

NEUTRON MEASUREMENTS

The neutron measurements performed using the TEPC were all in good agreement with reference measurements. Table 12 summarizes the average ratios of TEPC measurements to the reference dose equivalents for the laboratory irradiations and the reactor measurements.

TABLE 12. Average Ratio of TEPC Dose Equivalent to Reference Dose Equivalent

<u>Irradiation</u>	<u>Kellerer Approximation</u>	<u>Borak Approximation</u>
^{252}Cf	0.91 ± 0.09	1.05 ± 0.14
Reactors	0.71 ± 0.15	0.86 ± 0.20

The ratio of the TEPC determined dose equivalents to reference dose equivalents could have been improved for reactor measurements if longer counting times and higher integral doses could have been attained. The measurements were constrained by the effects of heat (upon the researchers as well as upon the instruments), ALARA, and the overall lack of locations with high neutron dose rates. Additionally, the heat appears to have affected the multisphere measurements at Site 1 by broadening the thermal neutron peak obtained from the LiI detector.

Examination of the remmeter data taken in conjunction with these measurements reveals that the SNOOPY remmeter responded 71% higher than the multispheres (1.71 ± 0.74) and approximately 100% higher than the TEPC (1.99 ± 0.78). These results are in excellent agreement with earlier results (Endres et al. 1981, Schwartz et al. 1982, Cummings et al. 1980). Schwartz published a value of 1.66 as the ratio of the responses of a cylindrical remmeter

(similar to the one used in this study) to bare and D_2O -moderated ^{252}Cf ($DE_{D_2O-Cf}/DE_{Bare Cf} = 1.66$, Schwartz et al. 1982). Further it was recommended by Schwartz et al. (1982) that remmeters be calibrated using the specified D_2O -moderated ^{252}Cf source. These data support that conclusion, but cautiously, as the average ratio of remmeter measurement to reference measurement carried with it a large standard deviation. (The remmeter used in this task had been calibrated using a bare ^{252}Cf source.)

GAMMA MEASUREMENTS

The gamma measurements performed with the TEPC were very poor. The main reason that the counter could not accurately assess gamma dose was that electronic noise limited the minimum event size that could be measured.

The electronic noise was caused by three major components of the TEPC system. First, since larger counters (5-in. diameter) were used to increase sensitivity and decrease stay time, there was a larger degree of electronic noise produced by the counter/preamp combination and long signal cables. Secondly, problems with the internal calibration sources and high voltages in self-contained TEPCs forced the use of the older style laboratory counters for reactor measurements, which introduced more noise from the external preamp and high voltage power supplies. (The problems associated with the self-contained TEPCs have been corrected on the later models which have since been produced by EG&G and Far West Technologies.) Third, research amplifiers were also slightly noisier due to the heat encountered inside the reactors.

The magnitude of this effect for gamma dose analysis is seen by examining the $y \cdot D(y)$, or $y^2 N(y)$ distributions for x rays published by Kliuga and Dvorak (1978) (Figure 9). The data need to be analyzed between 0.1 and 20 keV/micrometer in order to accurately assess dose.

The best measurement that the authors could obtain for this study, using a low noise, 2-1/4-in. diameter TEPC in a low-scatter calibration facility, is depicted in Figure 10 (from appendix, Figure A.12). The lowest event size which could be reached proved to be 0.3 keV/micrometer. (The peak at ~ 0.2 keV/micrometer is electronic noise.) The constrictions of heat and vibration made that goal unattainable for the reactor measurements. At present, the TEPC can not be used to accurately measure dose from photon induced events in reactor environments for the foregoing reasons.

FIGURE 9. The Distribution $y^2 N(y)$ as a Function of y for a 1- μ m Simulated Cavity at Eight Photon Energies (From Kliagua and Dvorak 1978)

FIGURE 10. $y^2 N(y)$ Distribution from a D_2O -Moderated ^{252}Cf Source

RECOMMENDATIONS

- Based on the performance of the TEPC compared to reference measurements, it is recommended that the TEPC is a superior alternative to multisphere measurements for accurately measuring absorbed neutron dose and determining neutron dose equivalent inside reactor containment.
- Remmeters used inside containment of power reactors responded higher than multisphere measurements by a factor of 1.71 ± 0.74 when the remmeters were calibrated with bare ^{252}Cf . Other measurements have been performed at the NBS in which remmeters responded 1.66 times higher to neutron fields from D_2O -moderated ^{252}Cf than to neutron fields from bare ^{252}Cf (Schwartz et al. 1982). Based on our findings and those results, it is recommended that remmeters which are to be used inside containment of nuclear power plants be (1) calibrated using a D_2O -moderated ^{252}Cf source or (2) corrected to account for energy dependence of the remmeter.
- It is recommended at this time that the TEPC not be used to assess absorbed gamma dose and gamma dose equivalent inside reactor containment.

REFERENCES

- Borak, T. B., and T. G. Stinchcomb. 1982. "Errors in Estimating Neutron Quality Factor Using Lineal Energy Distributions Measured in Tissue-Equivalent Proportional Counters." Health Phys. 43:2.
- Cosack, M., and H. Lesiecki. 1981. "Dependence of the Response of Eight Neutron Dose Equivalent Survey Meters with Regard to the Energy and Direction of Incident Neutrons." Contributed to the Fourth Symposium on Neutron Dosimetry, Neuherberg, Germany.
- Cummings, F. M., G. W. R. Endres and L. W. Brackenbush. 1983. Neutron Dosimetry at Commercial Nuclear Plants--Final Report of Subtask B: Dosimeter Response. NUREG/CR-1769, U.S. Nuclear Regulatory Commission, Washington, D.C.
- Endres, G. W. R., J. M. Aldrich, L. W. Brackenbush and R. V. Griffith. 1981. Neutron Dosimetry at Commercial Nuclear Plants--Final Report of Subtask A: Reactor Containment Measurements. NUREG/CR-1769, U.S. Nuclear Regulatory Commission, Washington, D.C.
- Evans, R. D. 1955. The Atomic Nucleus. McGraw-Hill, Inc., New York.
- Evans, R. D. 1968. "x-Ray and γ -Ray Interactions," in Radiation Dosimetry, Vol. 1, F. H. Attix, W. C. Roesch and E. Tochilin, eds. Academic Press, New York.
- Failla, G., and H. H. Rossi. 1950. "Dosimetry of Ionizing Particles." Am. J. Roentgenol. 64:489.
- Glass, W. A., and D. N. Samsky. 1967. "Ionization in Thin Tissue-Like Gas Layers by Monoenergetic Protons." Rad. Res. 32:138.
- Hankins, D. E. 1977. "Energy Dependence Measurements of Rem-Meters and Albedo Dosimeters at Neutron Energies of Thermal and Between 2 keV and 5.67 MeV," p.553 in Proceedings of the International Radiation Protection Association's IV International Congress, Paris, France.
- International Commission on Radiological Protection (ICRP). 1973. Data for Protection Against Ionizing Radiation From External Sources: Supplement to ICRP Publication 15. ICRP Publication 21, International Commission on Radiological Protection, 7910 Woodmont Avenue, Washington, D.C.
- International Commission on Radiological Units and Measurements (ICRU). 1962. Physical Aspects of Irradiation. ICRU Publication 10b, 7910 Woodmont Avenue, Washington, D.C.
- International Commission on Radiological Units and Measurements (ICRU). 1969. Linear Energy Transfer. ICRU Publication 16, 7910 Woodmont Avenue, Washington, D.C.

- International Commission on Radiological Units and Measurements (ICRU). 1976. Radiation Protection Instrumentation and Its Application. ICRU Publication 20, 7910 Woodmont Avenue, Washington, D.C.
- International Commission on Radiological Units and Measurements (ICRU). 1977. Neutron Dosimetry for Biology and Medicine. ICRU Publication 26, 7910 Woodmont Avenue, Washington, D.C.
- Kellerer, A. 1970. "Analysis of Pattern of Energy Deposition," in Microdosimetry, Second Symposium, EURATOM Report EUR4452, d-f-e, EURATOM, Brussels.
- Kliuga, P., and R. Dvorak. 1978. "Microdosimetric Measurements of Ionization by Monoenergetic Photons." Rad. Res. 73:1-20.
- Knoll, G. F. 1979. Radiation Detection and Measurement. John Wiley and Sons, New York.
- McDonald, J. C., R. V. Griffith, P. Plato and J. Miklos. 1983. Measurements of Gamma-Ray Dose From a Moderated ^{252}Cf Source. NUREG/CR-2957, U.S. Nuclear Regulatory Commission, Washington, D.C.
- National Bureau of Standards (NBS). 1961. Measurements of Absorbed Dose of Neutrons, and of Mixtures of Neutrons and Gamma Rays. NBS Publication 25, Department of Commerce, Washington, D.C.
- Srdoc, D. 1970. "A miniature X-Ray Calibration Tube." In Annual Report on Research Project, NYO-2740-5, pg. 22, Radiological Research Laboratory, Columbia University, New York.
- Relative Biological Effectiveness Committee. 1963. "Report of the RBE Committee to the International Commissions on Radiological Protection and on Radiological Units and Measurements." Health Phys. 9:4(357).
- Rossi, H. H. 1968. "Microscopic Energy Distribution in Irradiated Matter," in Radiation Dosimetry, Vol. 1, F. H. Attix, W. C. Roesch and E. Tochilin, eds. Academic Press, New York.
- Schwartz, R. B., and C. M. Eisenhauer. 1980. The Design and Construction of a D_2O -Moderated ^{252}Cf Source for Calibrating Neutron Personnel Dosimeters Used at Nuclear Power Reactors. NUREG/CR-1204, U.S. Nuclear Regulatory Commission, Washington, D.C.
- Schwartz, R. B., G. W. R. Endres and F. M. Cummings. 1982. Neutron Dosimeter Performance and Associated Calibrations at Nuclear Power Plants. NUREG/CR-2233, U.S. Nuclear Regulatory Commission, Washington, D.C.
- Stoddard, D. H., and H. E. Hootman. 1971. ^{252}Cf Shielding Guide. U.S.A.E.C. Report DP-1246.

APPENDIX

SUMMARY NEUTRON MEASUREMENTS

TABLE A.1. NBS Bare ^{252}Cf Neutron Measurements

<u>Source #</u>	<u>Emission Rate (n/sec)</u>	<u>Neutron DE Rate at 1 m (mrem/hr)</u>	<u>Date</u>
NS-79	4.13×10^8	394	3/28/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
502	1.0	12.7	3600

<u>Absorbed^(a) Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
$59.4 \pm 3.48^{(b)}$	8.8	523	10.0	594

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
353	0.2858	1.13×10^6	1.10×10^8

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
27.7	50.4	44.8

(a) Dose rate at 81.4 cm.

(b) One standard deviation from Poisson statistics.

FIGURE A.1. Raw Data for NBS Bare ^{252}Cf Neutron Measurement

FIGURE A.2. Y^2 Distribution for NBS Bare ^{252}Cf Neutron Measurement

TABLE A.2. NBS Bare ^{252}Cf - Gamma Measurement

		Gamma (a) DE Rate at 1 m (mrem/hr)		Date
Source #				
NS-79		42		3/28/83

TEPC #	Site Equivalent Diameter (micrometers)	TEPC Diameter (cm)	Live Time (sec)
502	1.0	12.7	3600

Absorbed (b) Dose Rate (mrad/hr)	Kellerer Approximation		Borak Approximation	
	Average Quality Factor	Dose Equivalent Rate (mrem/hr)	Average Quality Factor	Dose Equivalent Rate (mrem/hr)
22.1 ± 2.76 (c)	1.0	22	1.2	26

Proton Drop Point Channel #	Calibration Constant (keV/micron/channel)	Total Neutron Events (Counts)	Total Neutron Dose Events (Counts x Channel)
2926	0.0345	9.18 × 10 ⁶	3.38 × 10 ⁸

Average Event Size (Frequency) (keV/micron)	Average Event Size (Dose) (keV/micron)	Average LET (Dose) (keV/micron)
1.3	2.2	2.0

(a) From Stoddard 1971.

(b) Dose rate at 81.4 cm.

(c) One standard deviation from Poisson statistics.

FIGURE A.3. Raw Data for NBS Bare ^{252}Cf Gamma Measurement

FIGURE A.4. Y^2 Distribution for NBS Bare ^{252}Cf Gamma Measurement

TABLE A.3. NBS D₂O-Moderated ²⁵²Cf - Neutron Measurement

<u>Source #</u>	<u>Emission Rate (n/sec)</u>	<u>DE Rate at 1 m (mrem/hr)</u>	<u>Date</u>
NS-86	8.91×10^8	205	3/28/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
502	1.0	12.7	6118

<u>Absorbed^(a) Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
$61.1 \pm 3.61^{(b)}$	9.2	565	10.4	637

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
351	0.2875	1.77×10^6	1.90×10^8

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
30.9	53.7	47.7

(a) Dose rate at 56.4 cm.

(b) One standard deviation from Poisson statistics.

FIGURE A.5. Raw Data for NBS D₂O-Moderated ²⁵²Cf Neutron Measurement

FIGURE A.6. Y^2 Distribution for NBS D₂O-Moderated ²⁵²Cf Neutron Measurement

TABLE A.4. NBS D₂O-Moderated ²⁵²Cf - Gamma Measurement

<u>Source #</u>	<u>DE Rate at 1 m^(a)</u> (mrem/hr)		<u>Date</u>
NS-86	116		3/28/83

<u>TEPC #</u>	<u>Site Equivalent Diameter</u> (micrometers)	<u>TEPC Diameter</u> (cm)	<u>Live Time</u> (sec)
502	1.0	12.7	6118

<u>Absorbed^(b)</u> <u>Dose Rate</u> (mrad/hr)	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate</u> (mrem/hr)	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate</u> (mrem/hr)
45.6 ± 3.97 ^(c)	1.0	46	1.4	65

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant</u> (keV/micron/channel)	<u>Total Gamma Events</u> (Counts)	<u>Total Gamma Dose Events</u> (Counts x Channel)
2909	0.0347	1.80 x 10 ⁷	1.15 x 10 ⁹

<u>Average Event Size (Frequency)</u> (keV/micron)	<u>Average Event Size (Dose)</u> (keV/micron)	<u>Average LET (Dose)</u> (keV/micron)
2.2	3.3	2.9

(a) From Stoddard 1971.

(b) Dose rate at 81.4 cm.

(c) One standard deviation from Poisson statistics.

FIGURE A.7. Raw Data for NBS D₂O-Moderated ²⁵²Cf Gamma Measurement

FIGURE A.8. Y^2 Distribution for NBS D₂O-Moderated ²⁵²Cf Gamma Measurement

TABLE A.5. PNL Cf-252 Neutron Measurement

<u>Source #</u>	<u>Emission Rate (n/sec)</u>	<u>Reference DE Rate (mrem/hr)</u>	<u>Date</u>
CF-3	1.083×10^7	43	10/04/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
502	2.0	12.7	18000

<u>Absorbed⁽¹⁾ Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
4.40 ± 0.19	8.1	36	9.8	43

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
667	0.1469	4.23×10^5	7.89×10^7

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
27.3	45.4	40.4

(1) One standard deviation from Poisson Statistics.

FIGURE A.9. Raw Data for PNL Bare ^{252}Cf Neutron Measurement

FIGURE A.10. Y^2 Distribution for PNL Bare ^{252}Cf Neutron Measurement.

TABLE A.6. PNL Cf-252 Gamma Measurement

Source #	Emission Rate (n/sec)	Reference DE Rate (mrem/hr)	Date
CF-3	1.083×10^7	$3^{(1)}$	10/04/83

TEPC #	Site Equivalent Diameter (micrometers)	TEPC Diameter (cm)	Live Time (sec)
502	2.0	12.7	18000

Absorbed ⁽²⁾ Dose Rate (mrad/hr)	Kellerer Approximation		Borak Approximation	
	Average Quality Factor	Dose Equivalent Rate (mrem/hr)	Average Quality Factor	Dose Equivalent Rate (mrem/hr)
0.89 ± 0.07	1.0	1	1.2	1

Proton Drop Point Channel #	Calibration Constant (keV/micron/channel)	Total Neutron Events (Counts)	Total Neutron Dose Events (Counts x Channel)
667	0.1469	1.77×10^6	1.60×10^8

Average Event Size (Frequency) (keV/micron)	Average Event Size (Dose) (keV/micron)	Average LET (Dose) (keV/micron)
1.3	2.0	1.8

(1) From Stoddard, 1971.

(2) One standard deviation from Poisson Statistics.

FIGURE A.11. Raw Data for PNL Bare ^{252}Cf Gamma Measurement

FIGURE A.12. Y^2 Distribution for PNL Bare ^{252}Cf Gamma Measurement

TABLE A.7. PNL D₂O-Moderated ²⁵²Cf - Neutron Measurement

<u>Source #</u>	<u>Emission Rate (n/sec)</u>	<u>Neutron DE Rate at 1 m (mrem/hr)</u>	<u>Date</u>
SR-Cf-249Z	2.40×10^8	170	9/22/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
183	1.0	5.7	5000

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
$22.1 \pm 0.47^{(a)}$	8.0	178	9.7	214

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
783	D.1379	1.20×10^5	2.38×10^7

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
27.4	45.1	40.1

(a) One standard deviation from Poisson statistics.

FIGURE A.13. Raw Data for PNL D₂O-Moderated ²⁵²Cf Neutron Measurement

FIGURE A.14. Y^2 Distribution for PNL D₂O-Moderated ²⁵²Cf Neutron Measurement

TABLE A.8. PNL D₂O-Moderated ²⁵²Cf - Gamma Measurement

<u>Source #</u>	<u>DE Rate at 1 m (mrem/hr)</u>		<u>Date</u>	
SR-CF-249Z	31 ^(a)		9/22/83	
<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>	
183	1.0	5.7	5000	
<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
23.9 ± 1.19 ^(b)	1.0	24	1.2	30
<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>	
14,251	0.0071	1.99 × 10 ⁶	2.50 × 10 ⁸	
<u>Average Event Size (Frequency) (keV/micron)</u>		<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>	
0.9		2.1	1.9	

(a) From McDonald, et al. 1983.

(b) One standard deviation from Poisson statistics.

FIGURE A.15. Raw Data for PNL D₂O-Moderated ²⁵²Cf Gamma Measurement

FIGURE A.16. Y^2 Distribution for PNL D₂O-Moderated ²⁵²Cf Gamma Measurement

TABLE A.9. Site 1 (BWR) Neutron Measurement 1

<u>Location</u>	<u>SNOOPY D/E Rate (mrem/hr)</u>	<u>Multisphere DE Rate at (mrem/hr)</u>	<u>Date</u>
1	300	-	12/29/B2

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
502	2.0	12.7	1000

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
13.2 ± 1.07 ^(a)	8.7	115	10.9	144

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
199	0.4925	5.37 x 10 ⁴	3.93 x 10 ⁶

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
36.1	49.7	44.2

(a) One standard deviation from Poisson statistics.

TABLE A.10. Site 1 (BWR) Gamma Measurement 1

		Reference ^(a) DE Rate at (mrem/hr)			Date
Location					
1		1200			12/29/82

TEPC #	Site Equivalent Diameter (micrometers)	TEPC Diameter (cm)	Live Time (sec)
502	2.0	12.7	1000

Absorbed Dose Rate (mrad/hr)	Kellerer Approximation		Borak Approximation	
	Average Quality Factor	Dose Equivalent Rate (mrem/hr)	Average Quality Factor	Dose Equivalent Rate (mrem/hr)
29.6 ± 10.6 ^(b)	2.2	59	2.9	79

Proton Drop Point Channel #	Calibration Constant (keV/micron/channel)	Total Neutron Events (Counts)	Total Neutron Dose Events (Counts x Channel)
199	0.4925	4.37 x 10 ⁵	8.00 x 10 ⁶

Average Event Size (Frequency) (keV/micron)	Average Event Size (Dose) (keV/micron)	Average LET (Dose) (keV/micron)
9.0	9.2	8.2

(a) Portable ion chamber.

(b) One standard deviation from Poisson statistics.

TABLE A.11. Site 1 (BWR) Neutron Measurement 2

<u>Location</u>	<u>SNOOPY DE Rate (mrem/hr)</u>	<u>Multisphere DE Rate (mrem/hr)</u>	<u>Date</u>
2	150-180	-	12/29/82

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
502	2.0	12.7	1000

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
6.48 ± 0.60 ^(a)	8.4	542	10.6	690

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
162	0.6049	2.71 x 10 ⁴	1.57 x 10 ⁶

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
35.1	47.2	42.0

(a) One standard deviation from Poisson statistics.

TABLE A.12. Site 1 (BWR) Gamma Measurement 2

		Reference ^(a) DE Rate at 1 m (mrem/hr)	Date
Location			
2		12D0	12/29/82

TEPC #	Site Equivalent Diameter (micrometers)	TEPC Diameter (cm)	Live Time (sec)
502	2.0	12.7	1000

Absorbed Dose Rate (mrad/hr)	Kellerer Approximation		Borak Approximation	
	Average Quality Factor	Dose Equivalent Rate (mrem/hr)	Average Quality Factor	Dose Equivalent Rate (mrem/hr)
14.7 ± 7.D1 ^(b)	2.4	36	3.3	4.8

Proton Drop Point Channel #	Calibration Constant (keV/micron/channel)	Total Neutron Events (Counts)	Total Neutron Dose Events (Counts x Channel)
162	D.6049	2.D4 x 10 ⁵	3.55 x 10 ⁶

Average Event Size (Frequency) (keV/micron)	Average Event Size (Dose) (keV/micron)	Average LET (Dose) (keV/micron)
10.5	10.6	9.4

(a) Portable ion chamber.

(b) One standard deviation from Poisson statistics.

TABLE A.13. Site 1 (BWR) Neutron Measurement 3

<u>Location</u>	<u>SNOOPY DE Rate (mrem/hr)</u>	<u>Multisphere DE Rate (mrem/hr)</u>	<u>Date</u>
3	2500	-	12/29/82

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
	0.5	5.7	1500

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
136.5 ± 27.1 ^(a)	9.1	1240	10.8	1480

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
78	1.323	1.73 × 10 ⁵	4.59 × 10 ⁶

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
35.2	52.3	46.5

(a) One standard deviation from Poisson statistics.

TABLE A.14. Site Gamma Measurement 3

		Reference ^(a) DE Rate at 1 m (mrem/hr)	Date	
Location				
3		1200	12/29/82	

TEPC #	Site Equivalent Diameter (micrometers)	TEPC Diameter (cm)	Live Time (sec)
	0.5	5.7	1500

Absorbed Dose Rate (mrad/hr)	Kellerer Approximation		Borak Approximation	
	Average Quality Factor	Dose Equivalent Rate (mrem/hr)	Average Quality Factor	Dose Equivalent Rate (mrem/hr)
0.0013±0.0006 ^(b)	2.4	0.003	3.2	0.004

Proton Drop Point Channel #	Calibration Constant (keV/micron/channel)	Total Neutron Events (Counts)	Total Neutron Dose Events (Counts x Channel)
78	1.323	6	44

Average Event Size (Frequency) (keV/micron)	Average Event Size (Dose) (keV/micron)	Average LET (Dose) (keV/micron)
9.7	10.3	9.2

(a) Portable ion chamber.

(b) One standard deviation from Poisson statistics.

TABLE A.15. Site 1 (BWR) Neutron Measurement 4

<u>Location</u>	<u>SNOOPY DE Rate (mrem/hr)</u>	<u>Multisphere DE Rate (mrem/hr)</u>	<u>Date</u>
4	330	-	12/29/82

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
502	2.0	12.7	1000

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
12.8 ± 1.52 ^(a)	8.5	109	10.6	136

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
123	0.7967	5.70 x 10 ⁴	2.36 x 10 ⁶

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
33.0	48.0	42.7

(a) One standard deviation from Poisson statistics.

TABLE A.16. Site 1 (BWR) Gamma Measurement 4

		Reference DE Rate (mrem/hr)	Date
Location			
4		1200	12/29/82

TEPC #	Site Equivalent Diameter (micrometers)	TEPC Diameter (cm)	Live Time (sec)
502	2.0	12.7	1000

Absorbed Dose Rate (mrad/hr)	Kellerer Approximation		Borak Approximation	
	Average Quality Factor	Dose Equivalent Rate (mrem/hr)	Average Quality Factor	Dose Equivalent Rate (mrem/hr)
$3.04 \pm 2.13^{(a)}$	2.8	9	3.9	12

Proton Drop Point Channel #	Calibration Constant (keV/micron/channel)	Total Neutron Events (Counts)	Total Neutron Dose Events (Counts x Channel)
123	0.7967	3.41×10^4	5.59×10^5

Average Event Size (Frequency) (keV/micron)	Average Event Size (Dose) (keV/micron)	Average LET (Dose) (keV/micron)
13.1	13.1	11.6

(a) One standard deviation from Poisson statistics.

TABLE A.17. Site 1 (BWR) Neutron Measurement 5

<u>Location</u>	<u>SNOOPY DE Rate (mrem/hr)</u>	<u>Multisphere DE Rate (mrem/hr)</u>	<u>Date</u>
5	100	49	12/29/82

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
502	2.0	12.7	3035

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
5.53 ± 0.52 ^(a)	8.8	486	11.2	618

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
137	0.7153	6.36 x 10 ⁴	3.44 x 10 ⁶

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
38.6	50.3	44.7

(a) One standard deviation from Poisson statistics.

TABLE A.18. Site 1 (BWR) Gamma Measurement 5

		Reference DE Rate (mrem/hr)	Date	
Location				
5		60	12/29/82	

TEPC #	Site Equivalent Diameter (micrometers)	TEPC Diameter (cm)	Live Time (sec)
502			

Absorbed Dose Rate (mrad/hr)	Kellerer Approximation		Borak Approximation	
	Average Quality Factor	Dose Equivalent Rate (mrem/hr)	Average Quality Factor	Dose Equivalent Rate (mrem/hr)
$0.40 \pm 0.20^{(a)}$	2.7	1	3.7	1

Proton Drop Point Channel #	Calibration Constant (keV/micron/channel)	Total Neutron Events (Counts)	Total Neutron Dose Events (Counts x Channel)
137	0.07153	1.44×10^4	2.46×10^5

Average Event Size (Frequency) (keV/micron)	Average Event Size (Dose) (keV/micron)	Average LET (Dose) (keV/micron)
12.3	12.3	11.0

(a) One standard deviation from Poisson statistics.

TABLE A.19. Site 2 (BWR) Neutron Measurement 1

<u>Location</u>	<u>SNOOPY DE Rate (mrem/hr)</u>	<u>Multisphere DE Rate (mrem/hr)</u>	<u>Date</u>
1	450	450	2/6/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
502	2.1	12.7	1000

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
36.5 ± 2.43 ^(a)	10.1	369	11.9	436

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
236	0.4144	1.29 × 10 ⁵	1.29 × 10 ⁷

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
41.4	60.5	53.8

(a) One standard deviation from Poisson statistics.

FIGURE A.17. Raw Data for Site 2 Neutron Measurement 1

FIGURE A.18. Y^2 Distribution for Site 2 Neutron Measurement 1

TABLE A.20. Site 2 Gamma Measurement 1

		Reference ^(a) DE Rate (mrem/hr)	Date	
Location				
1		470	2/6/83	

TEPC #	Site Equivalent Diameter (micrometers)	TEPC Diameter (cm)	Live Time (sec)	
502	2.1	12.7	1000	

Absorbed Dose Rate (mrad/hr)	Kellerer Approximation		Borak Approximation	
	Average Quality Factor	Dose Equivalent Rate (mrem/hr)	Average Quality Factor	Dose Equivalent Rate (mrem/hr)
232 ± 30.7 ^(b)	1.0	232	1.3	304

Proton Drop Point Channel #	Calibration Constant (keV/micron/channel)	Total Neutron Events (Counts)	Total Neutron Dose Events (Counts x Channel)
1467	0.0667	1.83 x 10 ⁷	5.09 x 10 ⁸

Average Event Size (Frequency) (keV/micron)	Average Event Size (Dose) (keV/micron)	Average LET (Dose) (keV/micron)
1.9	2.8	2.5

(a) Portable ion chamber.

(b) One standard deviation from Poisson statistics.

FIGURE A.19. Raw Data for Site 2 Gamma Measurement 1

FIGURE A.20. y^2 Distribution for Site 2 Gamma Measurement 1

TABLE A.21. Site 2 Neutron Measurement 2

<u>Location</u>	<u>SNOOPY DE Rate (mrem/hr)</u>	<u>Multisphere DE Rate at (mrem/hr)</u>	<u>Date</u>
2	450	450	2/6/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
502	2.1	12.7	9301

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
41.5 ± 3.21 ^(a)	10.9	450	12.3	511

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
156	0.6269	1.37 x 10 ⁶	9.01 x 10 ⁷

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
41.4	66.7	59.3

(a) One standard deviation from Poisson statistics.

FIGURE A.21. Raw Data for Site 2 Neutron Measurement 2

FIGURE A.22. Y^2 Distribution for Site 2 Neutron Measurement 2

TABLE A.22. Site 2 Gamma Measurement 2

		Reference ^(a) DE Rate (mrem/hr)	Date	
Location				
2		470	2/6/83	
TEPC #	Site Equivalent Diameter (micrometers)	TEPC Diameter (cm)	Live Time (sec)	
502	2.1	12.7	8030	
Absorbed Dose Rate (mrad/hr)	Kellerer Approximation Average Quality Factor	Dose Equivalent Rate (mrem/hr)	Borak Approximation Average Quality Factor	Dose Equivalent Rate (mrem/hr)
70.7 ± 8.23 ^(b)	1.0	71	1.4	100
Proton Drop Point Channel #	Calibration Constant (keV/micron/channel)	Total Neutron Events (Counts)	Total Neutron Dose Events (Counts x Channel)	
1506	0.0649	3.31 x 10 ⁷	1.28 x 10 ⁹	
Average Event Size (Frequency) (keV/micron)	Average Event Size (Dose) (keV/micron)	Average LET (Dose) (keV/micron)		
2.5	3.4	3.0		

(a) Portable ion chamber.

(b) One standard deviation from Poisson statistics.

FIGURE A.23. Raw Data for Site 2 Gamma Measurement 2

FIGURE A.24. Y^2 Distribution for Site 2 Gamma Measurement 2

TABLE A.23. Site 2 Neutron Measurement 3

<u>Source #</u>	<u>SNOOPY DE Rate (mrem/hr)</u>	<u>Multisphere DE Rate at (mrem/hr)</u>	<u>Date</u>
3	-	-	2/6/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
501	2.1	12.7	1460

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
1.81 ± 0.15 ^(a)	9.5	17	11.7	21

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
173	0.5653	9.57 x 10 ³	6.85 x 10 ⁴

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
40.5	56.0	49.8

(a) One standard deviation from Poisson statistics.

FIGURE A.25. Raw Data for Site 2 Neutron Measurement 3

FIGURE A.26. Y^2 Distribution for Site 2 Neutron Measurement 3

TABLE A.24. Site 2 Gamma Measurement 3

<u>Location</u>		<u>Reference DE Rate (mrem/hr)</u>	<u>Date</u>	
3		-	2/6/83	

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
502	2.1	12.7	1300

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
113 ± 28.9 ^(a)	1.0	113	1.2	132

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
796	D.1229	9.15 x 10 ⁶	1.75 x 10 ⁸

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
2.4	2.6	2.3

(a) Portable ion chamber.

FIGURE A.27. Raw Data for Site 2 Gamma Measurement 3

FIGURE A.28. Y^2 Distribution for Site 2 Gamma Measurement 3

TABLE A.25. Site 2 Neutron Measurement 4

<u>Source #</u>	<u>SNOOPY DE Rate (mrem/hr)</u>	<u>Multisphere OE Rate (mrem/hr)</u>	<u>Date</u>
4	-	-	2/6/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
502	2.1	12.7	1021

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
4.49 ± 0.38 ^(a)	9.8	44	11.7	53

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
152	0.6434	1.65 x 10 ⁴	1.04 x 10 ⁶

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
40.7	58.1	51.6

(a) One standard deviation from Poisson statistics.

FIGURE A.29. Raw Data Site 2 Neutron Measurement 4

FIGURE A.30. Y^2 Distribution for Site 2 Neutron Measurement 4

TABLE A.26. Site 2 Gamma Measurement 4

		Reference DE Rate (mrem/hr)	Date	
Location				
4		-	2/6/83	
TEPC #	Site Equivalent Diameter (micrometers)	TEPC Diameter (cm)	Live Time (sec)	
502	2.1	12.7	900	
Absorbed Dose Rate (mrad/hr)	Kellerer Approximation		Borak Approximation	
	Average Quality Factor	Dose Equivalent Rate (mrem/hr)	Average Quality Factor	Dose Equivalent Rate (mrem/hr)
201 ± 49.9 ^(a)	1.0	201	1.1	226
Proton Drop Point Channel #	Calibration Constant (keV/micron/channel)	Total Neutron Events (Counts)	Total Neutron Dose Events (Counts x Channel)	
817	0.1197	1.17 × 10 ⁷	2.22 × 10 ⁸	
Average Event Size (Frequency) (keV/micron)		Average Event Size (Dose) (keV/micron)	Average LET (Dose) (keV/micron)	
2.3		2.5	2.2	

(a) Portable ion chamber.

FIGURE A.31. Raw Data for Site 2 Gamma Measurement 4

FIGURE A.32. Y^2 Distribution for Site 2 Gamma Measurement 4

TABLE A.27. Site 3 Neutron Measurement 1

<u>Source #</u>	<u>SNOOPY DE Rate (mrem/hr)</u>	<u>Multisphere DE Rate (mrem/hr)</u>	<u>Date</u>
1	80	84	8/1/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
185	1.0	12.7	1800

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
5.58 ± 0.40 ^(a)	9.7	54	11.9	66

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
219	0.4607	3.58 x 10 ⁴	3.19 x 10 ⁶

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
41.1	57.4	51.0

(a) One standard deviation from Poisson statistics.

TABLE A.28. Site 3 Gamma Measurement 1

	<u>Location</u>	<u>Reference DE Rate (mrem/hr)</u>	<u>Date</u>	
	1	12 ^(a)	8/1/83	
<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>	
185	1.0	12.7	1800	
<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Borak Approximation Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
1.4 ± 0.27 ^(b)	1.9	3	2.5	4
<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>	
216	0.4607	8.05 x 10 ⁴	8.24 x 10 ⁵	
<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>		
4.7	7.4	6.6		

(a) Portable ion chamber.

(b) One standard deviation from Poisson statistics.

FIGURE A.33. Raw Data for Site 3 - Location 1

FIGURE A.34. Y^2 Distribution for Site 3 - Location 1

TABLE A.29. Site 3 Neutron Measurement 2

<u>Source #</u>	<u>SNOOPY DE Rate (mrem/hr)</u>	<u>Multisphere DE Rate at (mrem/hr)</u>	<u>Date</u>
2	55	37	8/1/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
185	1.0	12.7	1800

<u>Absorbed Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
2.59 ± 0.18 ^(a)	9.9	26	11.3	29

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
224	0.4504	2.01 x 10 ⁴	1.52 x 10 ⁶

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
33.9	58.8	52.3

(a) One standard deviation from Poisson statistics.

TABLE A.30. Site 3 Gamma Measurement 2

		Reference DE Rate (mrem/hr)	Date	
Location				
2		50 ^(a)	8/1/83	
TEPC #	Site Equivalent Diameter (micrometers)	TEPC Diameter (cm)	Live Time (sec)	
185	1.0	12.7	1800	
Absorbed Dose Rate (mrad/hr)	Kellerer Approximation		Borak Approximation	
	Average Quality Factor	Dose Equivalent Rate (mrem/hr)	Average Quality Factor	Dose Equivalent Rate (mrem/hr)
1.0 ± 0.25 ^(b)	1.2	1	1.7	2
Proton Drop Point Channel #	Calibration Constant (keV/micron/channel)	Total Neutron Events (Counts)	Total Neutron Dose Events (Counts x Channel)	
224	0.4504	8.24 x 10 ⁴	5.82 x 10 ⁵	
Average Event Size (Frequency) (keV/micron)		Average Event Size (Dose) (keV/micron)	Average LET (Dose) (keV/micron)	
3.2		4.3	3.8	

(a) Portable ion chamber.

(b) One standard deviation from Poisson statistics.

FIGURE A.35. Raw Data for Site 3 - Location 2

FIGURE A.36. Y^2 Distribution for Site 3 - Location 2

TABLE A.31. Site 4 (PWR) Neutron Measurement 1

<u>Location</u>	<u>SNOOPY (min/hr)</u>	<u>Reference DE Rate (mrem/hr)</u>	<u>Date</u>
1	27	17	8/18/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
185	2.0	12.7	13096

<u>Absorbed⁽¹⁾ Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
0.95 ± 0.07	8.4	8	10.5	10

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Neutron Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
258	0.0310	5.600E + 004	4.792E + 006

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
32.5	47.7	42.4

(1) One standard deviation from Poisson Statistics.

TABLE A.32. Site 4 (PWR) Gamma Measurement 1

<u>Location</u>	<u>Reference DE Rate (mrem/hr)</u>	<u>Date</u>
1	0	8/18/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
185	2.0	12.7	13096

<u>Absorbed⁽¹⁾ Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
3.02 ± 1.36	1.0	3	1.4	4

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Gamma Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
258	0.0310	1.761E+006	1.527E+007

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
3.3	3.6	3.2

(1) One standard deviation from Poisson Statistics.

FIGURE A.37. Raw Data for Site 4 - Location 1 Neutron Measurement

FIGURE A.38. γ^2 Distribution for Site 4 - Location 1 Neutron Measurement

TABLE A.33. Site 4 (PWR) Neutron Measurement 2

<u>Location</u>	<u>SNOOPY (min/hr)</u>	<u>Reference DE Rate (mrem/hr)</u>	<u>Date</u>
2	15	12	8/17/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
185	2.0	12.7	67882

<u>Absorbed⁽¹⁾ Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
0.90 ± 0.06	8.5	8	10.8	11

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Gamma Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
261	0.0307	2.487E+005	2.393E+007

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
36.1	48.3	42.9

(1) One standard deviation from Poisson Statistics.

TABLE A.34. Site 4 (PWR) Gamma Measurement 2

<u>Location</u>	<u>Reference DE Rate (mrem/hr)</u>	<u>Date</u>
2	0	8/17/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
185	2.0	12.7	67882

<u>Absorbed⁽¹⁾ Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
3.57 ± 1.09	1.8	6	2.3	8

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Gamma Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
261	0.0307	5.622E+006	9.438E+007

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
6.3	6.7	6.0

(1) One standard deviation from Poisson Statistics.

FIGURE A.39. Raw Data for Site 4 - Location 2 Neutron Measurement

FIGURE A.40. Y^2 Distribution for Site 4 - Location 2 Neutron Measurement

TABLE A.35. Site 4 (PWR) Gamma Measurement 3

<u>Location</u>	<u>Reference DE Rate (mrem/hr)</u>	<u>Date</u>
3	0	8/15/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
185	2.0	12.7	4415

<u>Absorbed⁽¹⁾ Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
8.27 ± 4.24	1.8	8	1.2	10

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Gamma Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
257	0.0311	1.954E+006	1.403E+007

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
2.7	3.0	2.6

(1) One standard deviation from Poisson Statistics.

TABLE A.36. Site 4 (PWR) Neutron Measurement 3

<u>Location</u>	<u>SNOOPY (min/hr)</u>	<u>Reference DE Rate (mrem/hr)</u>	<u>Date</u>
3	33	16	8/15/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
185	2.0	12.7	4415

<u>Absorbed⁽¹⁾ Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
1.28 ± 0.09	8.2	11	10.3	13

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Gamma Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
257	D.0311	2.666E+004	2.167E+006

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
31.0	46.4	41.3

(1) One standard deviation from Poisson Statistics.

FIGURE A.41. Raw Data for Site 4 - Location 3 Neutron Measurement

FIGURE A.42. Y^2 Distribution for Site 4 - Location 3 Neutron Measurement

TABLE A.37. Site 4 (PWR) Gamma Measurement 3

<u>Location</u>	<u>Reference DE Rate (mrem/hr)</u>		<u>Date</u>	
4	0		8/16/83	
<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>	
185	2.0	12.7	6100	
<u>Absorbed⁽¹⁾ Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
8.22 ± 4.23	1.3	11	1.8	15
<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Gamma Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>	
166	0.0482	1.756E+006	1.244E+007	
<u>Average Event Size (Frequency) (keV/micron)</u>		<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>	
4.2		4.6	4.1	

(1) One standard deviation from Poisson Statistics.

TABLE A.38. Site 4 (PWR) Neutron Measurement 4

<u>Location</u>	<u>SNOOPY (min/hr)</u>	<u>Reference DE Rate (mrem/hr)</u>	<u>Date</u>
4	68	35	8/16/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
185	2.0	12.7	6100

<u>Absorbed⁽¹⁾ Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
2.99 ± 0.23	9.6	29	11.7	35

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Gamma Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
166	0.0482	7.073+004	4.526E+006

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
37.8	56.8	50.5

(1) One standard deviation from Poisson Statistics.

FIGURE A.43. Raw Data for Site 4 - Location 4 Neutron Measurement

FIGURE A.44. γ^2 Distribution for Site 4 - Location 4 Neutron Measurement

TABLE A.39. Site 4 (PWR) Gamma Measurement 3

<u>Location</u>	<u>Reference DE Rate (mrem/hr)</u>		<u>Date</u>
5	0		8/17/83

<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>
185	2.0	12.7	59151

<u>Absorbed⁽¹⁾ Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
1.95 ± 0.67	1.3	3	1.8	4

<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Gamma Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>
205	0.0390	4.205E+006	3.540E+007E

<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>
4.0	4.7	4.2

(1) One standard deviation from Poisson Statistics.

TABLE A.40. Site 4 (PWR) Neutron Measurement 5

<u>Location</u>	<u>SNOOPY (min/hr)</u>	<u>Reference DE Rate (mrem/hr)</u>	<u>Date</u>	
5	53	16	8/17/83	
<u>TEPC #</u>	<u>Site Equivalent Diameter (micrometers)</u>	<u>TEPC Diameter (cm)</u>	<u>Live Time (sec)</u>	
185	2.0	12.7	59151	
<u>Absorbed⁽¹⁾ Dose Rate (mrad/hr)</u>	<u>Kellerer Approximation</u>		<u>Borak Approximation</u>	
	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>	<u>Average Quality Factor</u>	<u>Dose Equivalent Rate (mrem/hr)</u>
1.32 ± 0.10	8.7	12	10.8	14
<u>Proton Drop Point Channel #</u>	<u>Calibration Constant (keV/micron/channel)</u>	<u>Total Gamma Events (Counts)</u>	<u>Total Neutron Dose Events (Counts x Channel)</u>	
205	0.0390	3.408+005	2.394E+007	
	<u>Average Event Size (Frequency) (keV/micron)</u>	<u>Average Event Size (Dose) (keV/micron)</u>	<u>Average LET (Dose) (keV/micron)</u>	
	33.6	49.9	44.4	

(1) One standard deviation from Poisson Statistics.

FIGURE A.45. Raw Data for Site 4 - Location 5 Neutron Measurement

FIGURE A.46. Y^2 Distribution for Site 4 - Location 5 Neutron Measurement

TABLE A.41. Summary of Multisphere Data

Site-Location	Total Neutron Flux (n/cm ² -sec)	Average Neutron Energy (keV)	Average Quality Factor	Dose Equivalent Rate (mrem/hr)
1-5	2010	160	7.1	90
2-1	10220	302	9.2	450
3-1	3480	49	4.7	40
3-2	6810	65	5.2	93
4-1	2380	20	3.3	17
4-2	1840	17	3.1	12
4-3	3510	3	2.2	16
4-4	5070	18	3.2	35
4-5	3680	2	2.2	16
PNL Bare ²⁵² Cf	88	1640	8.9	8.6 ^(a)

(a) At 1 meter, dose equivalent rate at 50 cm = 35 mrem/hr.

TABLE A.42. Multisphere Data for Site 1 - Location 5

Detector Responses (Measured and Calculated)							
Number of Iterations = 96				Error = 3.0%			
Detector Responses (Measured and Calculated)							
	Bare	Cd-Cover	3-inch	5-inch	8-inch	1D-inch	12-inch
Meas	462.60	378.20	2449.20	2980.70	1497.50	686.10	311.60
Calc	521.80	325.38	2647.83	2960.22	1296.48	698.05	316.15

Bin No.	Energy (MeV)	Flux (n/cm ² -s)	Differential	
			Dose (rad/hr)	Dose Equiv (rem/hr)
1	2.57E-007	1.00E+002	1.90E-004	4.04E-004
2	5.48E-007	7.28E+000	1.60E-005	3.33E-005
3	1.06E-006	7.10E+000	1.58E-005	3.31E-005
4	2.25E-006	1.82E+001	4.02E-005	8.52E-005
5	4.77E-006	3.30E+001	7.20E-005	1.54E-004
6	1.01E-005	4.44E+001	9.59E-005	2.07E-004
7	2.14E-004	5.15E-001	1.11E-004	2.35E-004
8	4.52E-005	5.97E+001	1.28E-004	2.66E-004
9	9.58E-005	5.82E-001	1.23E-004	2.52E-004
10	2.03E-004	5.24E+001	1.08E-004	2.18E-004
11	4.34E-004	5.67E+001	1.11E-004	2.26E-004
12	9.13E-004	5.93E+001	1.12E-004	2.26E-004
13	1.92E-003	7.24E+001	1.34E-004	2.70E-004
14	4.07E-003	8.56E+001	1.57E-004	3.15E-004
15	8.62E-003	9.74E+001	3.57E-004	3.57E-004
16	1.83E-002	1.28E+002	2.59E-004	7.15E-004
17	3.86E-002	1.72E+002	4.11E-004	1.75E-003
18	8.18E-002	2.25E+002	6.36E-004	4.27E-003
19	1.67E-001	2.54E+002	9.50E-004	8.08E-003
20	3.37E-001	2.37E+002	1.24E-003	1.24E-002
21	6.79E-001	1.47E+002	1.19E-003	1.29E-002
22	1.39E+000	3.64E+001	4.46E-004	4.40E-003
23	2.78E+000	6.59E+000	1.00E-004	8.16E-004
24	5.54E+000	9.20E-001	1.91E-005	1.34E-005
25	1.12E+001	1.21E-001	2.88E-006	1.99E-005
26	2.04E+001	5.95E-002	1.95E-006	1.35E-005
Total		2.01E+003	6.84E-003	4.88E-002

Total Flux = 2.01E+003 n/cm²-sec
 Dose Rate = 6.84E-003 rad/hr
 Dose Equivalent Rate = 4.88E-002 rem/hr
 Ave. Quality Factor = 7.12
 Average Energy = 0.16 MeV

FIGURE A.47. Site 1 - Location 5 Dose Equivalent Spectrum

FIGURE A.48. Site 1 - Location 5 Neutron Flux Spectrum

TABLE A.43. Multisphere Data for Site 2 - Locations 1 and 2

		Number of Iterations = 501				Error = 7.5%	
		Detector Responses (Measured and Calculated)					
	Bare	Cd-Cover	3-inch	5-inch	8-inch	10-inch	12-inch
Meas	3101.900	833.400	10406.399	14012.300	9650.399	5494.400	2165.900
Calc	3104.687	835.077	10035.953	15578.985	8738.924	5038.768	2378.713

Bin No.	Energy (MeV)	Flux (n/cm ² -s)	Differential	
			Dose (rad/hr)	Dose Equiv (rem/hr)
1	2.57E-07	1.25E+03	2.37E-03	5.06E-03
2	5.48E-07	3.60E+01	7.90E-05	1.65E-04
3	1.06E-06	3.24E+01	7.21E-05	1.51E-04
4	2.25E-06	3.62E+01	8.00E-05	1.69E-04
5	4.77E-06	4.04E+01	8.83E-05	1.89E-04
6	1.01E-05	4.68E+01	1.01E-04	2.19E-04
7	2.14E-05	5.54E+01	1.19E-04	2.53E-04
8	4.52E-05	7.41E+01	1.58E-04	3.30E-04
9	9.58E-05	8.20E+01	1.74E-04	3.55E-04
10	2.03E-04	9.90E+01	4.12E-04	4.52E-02
11	4.34E-04	1.18E+02	2.32E-04	4.70E-04
12	9.13E-04	1.41E+02	2.66E-04	5.37E-04
13	1.92E-03	1.63E+02	3.02E-04	6.09E-04
14	4.07E-03	1.89E+02	3.46E-04	6.94E-04
15	8.62E-03	2.16E+02	3.92E-04	7.93E-04
16	1.82E-02	2.58E+02	5.23E-04	1.44E-03
17	3.86E-02	3.42E+02	8.18E-04	3.49E-03
18	8.18E-02	5.61E+02	1.58E-03	1.04E-02
19	1.67E-01	1.15E+03	4.31E-03	3.66E-02
20	3.37E-01	2.50E+03	1.31E-02	1.31E-01
21	6.79E-01	2.74E+03	2.21E-02	2.41E-01
22	1.39E-01	8.56E+01	1.05E-03	1.03E-02
23	2.78E+00	6.35E-01	9.65E-06	7.87E-05
24	5.54E+00	7.53E-04	1.57E-08	1.10E-07
25	1.12E+01	3.35E-06	7.98E-11	5.51E-10
26	2.04E+01	2.89E-11	9.46E-16	6.55E-15
Total		1.02E+04	4.85E-02	4.45E-01

Total Flux = 1.022E+04 n/cm²-sec
 Dose Rate = 4.849E-02 rad/hr
 Dose Equivalent Rate = 4.450E-01 rem/hr
 Quality Factor = 9.178 rem/rad
 Average Energy = 0.302 MeV

FIGURE A.49. Site 2 Neutron Flux Spectrum

FIGURE A.50. Site 2 Dose Equivalent Spectrum

TABLE A.44. Multisphere Data for Site 3 - Location 1

		Number of Iterations = 501				Error = 4.0%	
		Detector Responses (Measured and Calculated)					
	Bare	Cd-Cover	3-inch	5-inch	8-inch	10-inch	12-inch
Meas	3290.410	1178.440	3338.920	3077.890	1366.730	585.740	255.020
Calc	3298.698	1175.656	3353.207	3123.955	1253.216	621.753	255.573

Bin No.	Energy (MeV)	Flux (n/cm ² -s)	Differential	
			Dose (rad/hr)	Dose Equiv (rem/hr)
1	2.57E-07	1.12E+03	2.12E-03	4.52E-03
2	5.48E-07	2.44E+02	5.34E-04	1.12E-03
3	1.06E-06	1.71E+02	3.79E-04	7.95E-04
4	2.25E-06	1.20E+02	2.65E-04	5.62E-04
5	4.77E-06	8.62E+01	1.88E-04	4.03E-04
6	1.01E-05	6.72E+01	1.45E-04	3.14E-04
7	2.14E-05	5.42E+01	1.16E-04	2.47E-04
8	4.52E-05	4.58E+01	9.78E-05	2.04E-04
9	9.58E-05	4.29E+01	9.10E-05	1.86E-05
10	2.03E-04	4.34E+01	8.91E-05	1.81E-04
11	4.34E-04	4.75E+01	9.34E-05	1.89E-04
12	9.13E-04	5.47E+01	1.03E-04	2.09E-04
13	1.92E-03	6.63E+01	1.23E-04	2.47E-04
14	4.07E-03	8.32E+01	1.52E-04	3.06E-04
15	8.62E-03	1.08E+02	1.96E-04	3.97E-04
16	1.82E-02	1.43E+02	2.90E-04	8.01E-04
17	3.86E-02	1.94E+02	4.64E-04	1.98E-03
18	8.18E-02	2.65E+02	7.48E-04	4.91E-03
19	1.67E-01	3.09E+02	1.16E-03	9.83E-03
20	3.37E-01	1.86E+02	9.73E-04	9.76E-03
21	6.79E-01	3.09E+01	2.50E-04	2.72E-03
22	1.39E-01	1.80E+00	2.21E-05	2.18E-04
23	2.78E+00	1.76E-01	2.68E-06	2.18E-05
24	5.54E+00	5.94E-03	1.24E-07	8.64E-07
25	1.12E+01	3.53E-04	8.43E-09	5.82E-08
26	2.04E+01	7.43E-09	2.43E-13	1.69E-12
Total		3.48E+03	8.60E-03	4.01E-02

Total Flux = 3.483E+03 n/cm²-sec
 Dose Rate = 8.598E-03 rad/hr
 Dose Equivalent Rate = 4.011E-02 rem/hr
 Quality Factor = 4.665 rem/rad
 Average Energy = 0.049 MeV

FIGURE A.51. Site 3 - Location 1 Dose Equivalent Spectrum

FIGURE A.52. Site 3 - Location 1 Neutron Flux Spectrum

TABLE A.45. Multisphere Data for Site 3 Location 2

		Number of Iterations = 501			Error = 5.5%		
		Detector Responses (Measured and Calculated)					
	Bare	Cd-Cover	3-inch	5-inch	8-inch	10-inch	12-inch
Meas	5737.510	2254.700	7243.490	6375.140	3114.110	1308.120	570.650
Calc	5760.709	2254.098	7128.765	6748.360	2745.175	1384.648	578.347

Bin No.	Energy (MeV)	Flux (n/cm ² -s)	Differential	
			Dose (rad/hr)	Dose Equiv (rem/hr)
1	2.57E-07	1.84E+03	3.49E-03	7.45E-03
2	5.48E-07	3.74E+02	8.19E-04	1.71E-03
3	1.06E-06	2.87E+02	6.37E-04	1.34E-03
4	2.25E-06	2.39E+02	5.27E-04	1.12E-03
5	4.77E-06	1.96E+02	4.28E-04	9.16E-04
6	1.01E-05	1.71E+02	3.71E-04	8.00E-04
7	2.14E-05	1.50E+02	3.23E-04	6.86E-04
8	4.52E-05	1.54E+02	3.29E-04	6.85E-04
9	9.58E-05	1.26E+02	2.68E-04	5.46E-04
10	2.03E-04	1.23E+03	2.52E-04	5.12E-04
11	4.34E-04	1.26E+02	2.47E-04	5.00E-04
12	9.13E-04	1.34E+02	2.53E-04	5.12E-04
13	1.92E-03	1.48E+02	2.74E-04	5.52E-04
14	4.07E-03	1.70E+02	3.12E-04	6.26E-04
15	8.62E-03	2.04E+02	3.69E-04	7.47E-04
16	1.82E-02	2.52E+02	5.10E-04	1.41E-03
17	3.86E-02	3.31E+02	7.91E-04	3.37E-03
18	8.18E-02	4.68E+02	1.32E-03	8.68E-03
19	1.67E-01	6.46E+02	2.42E-03	2.05E-02
20	3.37E-01	5.43E+02	2.84E-03	2.85E-02
21	6.79E-01	1.20E+02	9.71E-04	1.06E-02
22	1.39E-01	5.99E+00	7.34E-05	7.23E-04
23	2.78E+00	3.79E-01	5.76E-06	4.69E-05
24	5.54E+00	7.69E-03	1.60E-07	1.12E-06
25	1.12E+01	3.06E-04	7.30E-09	5.04E-08
26	2.04E+01	5.80E-09	1.90E-13	1.32E-12
Total		6.81E+03	1.78E-02	9.26E-02

Total Flux = 6.811E+03 n/cm²-sec
 Dose Rate = 1.783E-02 rad/hr
 Dose Equivalent Rate = 9.255E-02 rem/hr
 Quality Factor = 5.191 rem/rad
 Average Energy = 0.065 MeV

FIGURE A.53. Site 3 - Location 2 Neutron Flux Spectrum

FIGURE A.54. Site 3 - Location 2 Dose Equivalent Spectrum

TABLE A.46. Site 4 Location 1

		Number of Iterations = 501			Error = 4.9%		
		Detector Responses (Measured and Calculated)					
	Bare	Cd-Cover	3-inch	5-inch	8-inch	10-inch	12-inch
Meas	2342.300	812.900	2382.400	1952.000	794.700	316.900	130.300
Calc	2349.164	810.258	2408.138	1968.304	707.625	337.043	133.902

Bin No.	Energy (MeV)	Flux (n/cm ² -s)	Differential	
			Dose (rad/hr)	Dose Equiv (rem/hr)
1	2.57E-07	8.21E+02	1.55E-03	3.32E-03
2	5.48E-07	1.31E+02	2.88E-04	6.02E-04
3	1.06E-06	1.01E+02	2.26E-04	4.74E-04
4	2.25E-06	8.38E+01	1.85E-04	3.92E-04
5	4.77E-06	6.74E+01	1.47E-04	3.15E-04
6	1.01E-05	5.93E+01	1.28E-04	2.77E-04
7	2.14E-05	5.36E+01	1.15E-04	2.45E-04
8	4.52E-05	4.98E+01	1.06E-04	2.22E-04
9	9.58E-05	5.05E+01	1.07E-04	2.18E-04
10	2.03E-04	5.30E+01	1.09E-04	2.21E-04
11	4.34E-04	5.82E+01	1.15E-04	2.32E-04
12	9.13E-04	6.55E+01	1.24E-04	2.50E-04
13	1.92E-03	7.51E+01	1.39E-04	2.80E-04
14	4.07E-03	8.72E+01	1.60E-04	3.21E-04
15	8.62E-03	1.02E+02	1.85E-04	3.74E-04
16	1.82E-02	1.18E+02	2.40E-04	6.62E-04
17	3.86E-02	1.34E+02	3.21E-04	1.37E-03
18	8.18E-02	1.39E+02	3.91E-04	2.57E-03
19	1.67E-01	1.02E+02	3.82E-04	3.25E-03
20	3.37E-01	2.80E+01	1.46E-04	1.47E-03
21	6.79E-01	1.44E+00	1.16E-05	1.27E-04
22	1.39E-01	2.28E-02	2.80E-07	2.75E-06
23	2.78E+00	9.00E-04	1.37E-08	1.11E-07
24	5.54E+00	1.56E-05	3.24E-10	2.27E-09
25	1.12E+01	6.12E-07	1.46E-11	1.01E-10
26	2.04E+01	1.17E-11	3.85E-16	2.66E-15
Total		2.38E+03	5.18E-03	1.72E-02

Total Flux = 2.382E+03 n/cm²-sec
 Dose Rate = 5.181E-03 rad/hr
 Dose Equivalent Rate = 1.719E-02 rem/hr
 Quality Factor = 3.317 rem/rad
 Average Energy = 0.020 MeV

FIGURE A.55. Site 4 - Location 1 Neutron Flux Spectrum

FIGURE A.56. Site 4 - Location 1 Dose Equivalent Spectrum

TABLE A.47. Site 4 Location 2

		Number of Iterations = 501			Error = 5.9%		
		Detector Responses (Measured and Calculated)					
	Bare	Cd-Cover	3-inch	5-inch	8-inch	10-inch	12-inch
Meas	1856.700	532.600	2693.500	1447.700	600.300	233.800	92.300
Calc	1861.488	530.514	1725.885	1440.054	522.069	247.359	97.822

Bin No.	Energy (MeV)	Flux (n/cm ² -s)	Differential	
			Dose (rad/hr)	Dose Equiv (rem/hr)
1	2.57E-07	7.22E+02	1.37E-03	2.91E-03
2	5.48E-07	8.23E+01	1.80E-04	3.77E-04
3	1.06E-06	6.21E+01	1.38E-04	2.90E-04
4	2.25E-06	5.20E+01	1.15E-04	2.43E-04
5	4.77E-06	4.09E+01	8.93E-05	1.91E-04
6	1.01E-05	3.62E+01	7.82E-05	1.69E-04
7	2.14E-05	3.32E+01	7.13E-05	1.52E-04
8	4.52E-05	3.03E+01	6.48E-05	1.35E-04
9	9.58E-05	3.31E+01	7.03E-05	1.43E-04
10	2.03E-04	3.63E+01	7.45E-05	1.51E-04
11	4.34E-04	4.19E+01	8.24E-05	1.67E-04
12	9.13E-04	4.94E+01	9.33E-05	1.88E-04
13	1.92E-03	5.92E+01	1.10E-04	2.21E-04
14	4.07E-03	7.14E+01	1.31E-04	2.62E-04
15	8.62E-03	8.62E+01	1.56E-04	3.16E-04
16	1.82E-02	1.02E+02	2.06E-04	5.69E-04
17	3.86E-02	1.15E+02	2.74E-04	1.17E-03
18	8.18E-02	1.11E+03	3.12E-04	2.05E-03
19	1.67E-01	6.42E+01	2.40E-04	2.04E-03
20	3.37E-01	9.05E+00	4.74E-05	4.75E-04
21	6.79E-01	1.21E+00	9.77E-07	1.06E-05
22	1.39E-01	2.91E-04	3.57E-09	3.52E-08
23	2.78E+00	2.52E-06	3.83E-11	3.12E-10
24	5.54E+00	1.30E-08	2.70E-13	1.89E-12
25	1.12E+01	2.32E-10	5.53E-15	3.82E-14
26	2.04E+01	3.67E-15	1.20E-19	8.32E-19
Total		1.84E+03	3.90E-03	1.33E-02

Total Flux = 1.837E+03 n/cm²-sec
 Dose Rate = 3.902E-03 rad/hr
 Dose Equivalent Rate = 1.224E-02 rem/hr
 Quality Factor = 3.136 rem/rad
 Average Energy = 0.017 MeV

FIGURE A.57. Site 4 - Location 2 Neutron Flux Spectrum

FIGURE A.58. Site 4 - Location 2 Dose Equivalent Spectrum

TABLE A.48. Site 4 Location 3

		Number of Iterations = 1001				Error = 10.2%	
		Detector Responses (Measured and Calculated)					
	Bare	Cd-Cover	3-inch	5-inch	8-inch	10-inch	12-inch
Meas	3615.400	1201.100	3540.300	2769.700	1080.100	399.300	134.200
Calc	3609.050	1197.642	3650.641	2654.959	876.147	406.770	159.029

Bin No.	Energy (MeV)	Flux (n/cm ² -s)	Differential	
			Dose (rad/hr)	Dose Equiv (rem/hr)
1	2.57E-07	1.30E+03	2.46E-03	5.25E-03
2	5.48E-07	1.54E+02	3.38E-04	7.07E-04
3	1.06E-06	1.30E+02	2.89E-04	6.07E-04
4	2.25E-06	1.51E+02	3.34E-04	7.09E-04
5	4.77E-06	9.10E+01	1.99E-04	4.26E-04
6	1.01E-05	8.46E+01	1.83E-04	3.95E-04
7	2.14E-05	8.35E+01	1.80E-04	3.82E-04
8	4.52E-05	6.57E+01	1.40E-04	2.93E-04
9	9.58E-05	1.00E+02	2.13E-04	4.34E-04
10	2.03E-04	1.20E+02	2.46E-04	5.00E-04
11	4.34E-04	1.47E+02	1.90E-04	5.88E-04
12	9.13E-04	1.74E+02	3.30E-04	6.66E-04
13	1.92E-03	1.99E+02	3.69E-04	7.44E-04
14	4.07E-03	2.11E+02	3.86E-04	7.76E-04
15	8.62E-03	2.05E+02	3.72E-04	7.52E-04
16	1.82E-02	1.67E+02	3.39E-04	9.36E-04
17	3.86E-02	9.71E+01	2.32E-04	9.89E-04
18	8.18E-02	2.28E+01	6.43E-05	4.22E-04
19	1.67E-01	5.44E-01	2.03E-06	1.73E-05
20	3.37E-01	4.28E-05	2.24E-10	2.25E-09
21	6.79E-01	4.02E-13	3.24E-18	3.53E-17
22	1.39E-01	5.89E-24	7.22E-29	7.11E-28
23	2.78E+00	1.72E-32	0.00E-01	0.00E-01
24	5.54E+00	0.00E-01	0.00E-01	0.00E-01
25	1.12E+01	0.00E-01	0.00E-01	0.00E-01
26	2.04E+01	0.00E-01	0.00E-01	0.00E-01
Total		3.51E+03	6.97E-03	1.56E-02

Total Flux = 3.505E+03 n/cm²-sec
 Dose Rate = 6.967E-03 rad/hr
 Dose Equivalent Rate = 1.559E-02 rem/hr
 Quality Factor = 2.237 rem/rad
 Average Energy = 0.003 MeV

FIGURE A.59. Site 4 - Location 3 Neutron Flux Spectrum

FIGURE A.60. Site 4 - Location 3 Dose Equivalent Spectrum

TABLE A.49. Site 4 Location 4

		Number of Iterations = 751			Error = 7.7%		
		Detector Responses (Measured and Calculated)					
	Bare	Cd-Cover	3-inch	5-inch	8-inch	10-inch	12-inch
Meas	4095.100	1623.300	5653.000	4835.700	2035.900	755.400	288.100
Calc	4105.420	1618.196	5732.531	4873.192	1688.466	798.184	314.841

Bin No.	Energy (MeV)	Flux (n/cm ² -s)	Differential	
			Dose (rad/hr)	Dose Equiv (rem/hr)
1	2.57E-07	1.30E+03	2.46E-03	5.26E-03
2	5.48E-07	2.94E+02	6.45E-04	1.35E-03
3	1.06E-06	2.10E+02	4.66E-04	9.78E-04
4	2.25E-06	1.72E+02	3.79E-04	8.04E-04
5	4.77E-06	1.20E+02	2.62E-04	5.60E-04
6	1.01E-05	1.02E+02	2.20E-04	4.75E-04
7	2.14E-05	8.99E+01	1.93E-04	4.11E-04
8	4.52E-05	8.38E+01	1.79E-04	3.73E-04
9	9.58E-05	8.81E+01	1.87E-04	3.82E-04
10	2.03E-04	9.89E+01	2.03E-04	4.12E-04
11	4.34E-04	1.20E+02	2.35E-04	4.76E-04
12	9.13E-04	1.50E+02	2.83E-04	5.72E-04
13	1.92E-03	1.92E+02	3.56E-04	7.17E-04
14	4.07E-03	2.50E+02	4.57E-04	9.18E-04
15	8.62E-03	3.25E+02	5.89E-04	1.19E-03
16	1.82E-02	4.08E+02	8.27E-04	2.28E-03
17	3.86E-02	4.78E+02	1.14E-03	4.87E-03
18	8.18E-02	4.25E+02	1.20E-03	7.89E-03
19	1.67E-01	1.56E+02	5.81E-04	4.94E-03
20	3.37E-01	4.27E+00	2.24E-05	2.25E-04
21	6.79E-01	1.31E-03	1.06E-08	1.15E-07
22	1.39E-01	1.25E-08	1.53E-13	1.51E-12
23	2.78E+00	1.17E-12	1.77E-17	1.45E-16
24	5.54E+00	1.63E-16	3.40E-21	2.38E-29
25	1.12E+01	2.67E-19	6.38E-24	4.40E-23
26	2.04E+01	2.53E-24	8.29E-29	5.74E-28
Total		5.07E+03	1.09E-02	3.51E-02

Total Flux = 5.067E+03 n/cm²-sec
 Dose Rate = 1.089E-03 rad/hr
 Dose Equivalent Rate = 3.508E-02 rem/hr
 Quality Factor = 3.220 rem/rad
 Average Energy = 0.018 MeV

FIGURE A.61. Site 4 - Location 4 Neutron Flux Spectrum

FIGURE A.62. Site 4 - Location 4 Dose Equivalent Spectrum

TABLE A.50. Site 4 Location 5

		Number of Iterations = 501				Error = 15.5%	
		Detector Responses (Measured and Calculated)					
	Bare	Cd-Cover	3-inch	5-inch	8-inch	10-inch	12-inch
Meas	3680.400	1262.000	3916.900	3118.200	1216.900	437.600	126.200
Calc	3662.544	1257.488	4119.240	2869.432	916.822	424.385	165.743

Bin No.	Energy (MeV)	Flux (n/cm ² -s)	Differential	
			Dose (rad/hr)	Dose Equiv (rem/hr)
1	2.57E-07	1.31E+03	2.47E-03	5.28E-03
2	5.48E-07	8.86E+01	1.94E-04	4.06E-04
3	1.06E-06	9.74E+01	2.17E-04	4.55E-04
4	2.25E-06	1.44E+02	3.18E-04	6.74E-04
5	4.77E-06	1.15E+02	2.50E-04	5.36E-04
6	1.01E-05	1.25E+02	2.70E-04	5.83E-04
7	2.14E-05	1.39E+02	2.99E-04	6.35E-04
8	4.52E-05	1.19E+02	2.55E-04	5.31E-04
9	9.58E-05	1.77E+02	3.75E-04	7.67E-04
10	2.03E-04	1.98E+02	4.06E-04	8.25E-04
11	4.34E-04	2.16E+02	4.06E-04	8.25E-04
12	9.13E-04	2.21E+02	4.18E-04	8.44E-04
13	1.92E-03	2.14E+02	3.97E-04	7.99E-04
14	4.07E-03	1.90E+02	3.48E-04	7.00E-04
15	8.62E-03	1.54E+02	2.80E-04	5.66E-04
16	1.82E-02	1.07E+02	2.16E-04	5.96E-04
17	3.86E-02	5.40E+01	1.29E-04	5.50E-04
18	8.18E-02	1.25E+01	3.52E-05	2.31E-04
19	1.67E-01	4.45E-01	1.66E-06	1.41E-05
20	3.37E-01	1.76E-04	9.23E-10	9.26E-09
21	6.79E-01	6.59E-11	5.32E-16	5.80E-15
22	1.39E-01	1.91E-19	2.34E-24	2.30E-23
23	2.78E+00	3.93E-26	5.98E-31	4.87E-30
24	5.54E+00	4.50E-32	0.00E-01	0.00E-01
25	1.12E+01	3.78E-36	0.00E-01	0.00E-01
26	2.04E+01	0.00E-01	0.00E-01	0.00E-01
Total		3.68E+03	7.31E-03	1.59E-02

Total Flux = 3.679E+03 n/cm²-sec
 Dose Rate = 1.585E-02 rad/hr
 Dose Equivalent Rate = 1.585E-02 rem/hr
 Quality Factor = 2.169 rem/rad
 Average Energy = 0.002 MeV

FIGURE A.63. Site 4 - Location 5 Neutron Flux Spectrum

FIGURE A.64. Site 4 - Location 5 Dose Equivalent Spectrum

TABLE A.51. PNL Bare ^{252}Cf

		Number of Iterations = 96			Error = 3.0%		
		Detector Responses (Measured and Calculated)					
	Bare	Cd-Cover	3-inch	5-inch	8-inch	10-inch	12-inch
Meas	9.700	2.300	51.000	133.300	138.100	102.400	67.600
Calc	9.710	2.289	52.583	130.539	130.480	103.020	70.469

Bin No.	Energy (MeV)	Flux (n/cm ² -s)	Differential	
			Dose (rad/hr)	Dose Equiv (rem/hr)
1	2.57E-07	4.12E+00	7.80E-06	1.66E-05
2	5.48E-07	7.57E-02	1.66E-07	3.47E-07
3	1.06E-06	6.65E-02	1.48E-07	3.10E-07
4	2.25E-06	7.12E-02	1.57E-07	3.33E-07
5	4.77E-06	7.79E-02	1.70E-07	3.65E-07
6	1.01E-05	8.69E-02	1.88E-07	4.06E-07
7	2.14E-05	9.96E-02	2.14E-07	4.55E-07
8	4.52E-05	1.16E-01	2.48E-07	5.18E-07
9	9.58E-05	1.43E-01	3.04E-07	6.20E-07
10	2.03E-04	1.78E-01	3.65E-07	7.41E-07
11	4.34E-04	2.26E-01	4.45E-07	9.01E-07
12	9.13E-04	2.95E-01	5.57E-07	1.13E-06
13	1.92E-03	3.89E-01	7.20E-07	1.45E-06
14	4.07E-03	5.13E-01	9.39E-07	1.89E-06
15	8.62E-03	6.67E-01	1.21E-06	2.45E-06
16	1.82E-02	8.95E-01	1.81E-06	5.01E-06
17	3.86E-02	1.25E+00	5.42E-06	3.56E-05
18	8.18E-02	1.92E+00	5.42E-06	3.56E-05
19	1.67E-01	2.65E+00	9.91E-06	8.43E-05
20	3.37E-01	3.55E+00	1.86E-05	1.86E-04
21	6.79E-01	1.53E+01	1.24E-04	1.35E-03
22	1.39E-01	2.62E+01	3.22E-04	3.17E-03
23	2.78E+00	2.51E+01	3.81E-04	3.10E-03
24	5.54E+00	3.75E+00	7.80E-05	5.45E-04
25	1.12E+01	5.45E-01	1.30E-05	8.97E-05
26	2.04E+01	1.25E-05	4.10E-10	2.84E-09
Total		8.83E+01	9.69E-04	8.60E-03

Total Flux = 8.928E+03 n/cm²-sec
 Dose Rate = 9.693E-04 rad/hr
 Dose Equivalent Rate = 8.604E-03 rem/hr
 Quality Factor = 8.877 rem/rad
 Average Energy = 1.644 MeV

FIGURE A.65. Neutron Flux for PNL Bare ²⁵²Cf

FIGURE A.66. Neutron Dose Equivalent for PNL Bare ²⁵²Cf

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