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The Performance of Low Pressure Tissue Equivalent Chambers and a New Method for Parameterizing the Dose Equivalent

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THE PERFORMANCE OF LOW PRESSURE TISSUE EQUIVALENT
CHAMBERS AND A NEW
METHOD FOR PARAMETERIZING THE DOSE EQUIVALENT

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ABSTRACT

The performance of spherical tissue equivalent chambers with equivalent diameters between 0.5μ and 2μ was tested experimentally using monoenergetic and polyenergetic neutron sources in the energy region of 10 keV to 14.5 MeV. Theoretical calculations were performed in order to obtain a simple algorithm for deriving the dose equivalent from the measured data. The algorithm relates the number of recoil particles to the dose equivalent, rather than having a one-to-one correspondence between the lineal energy and the linear energy transfer of the recoil particles. The calculations took into account neutron interactions with hydrogen atoms in the chamber wall as well as in the gas, and also the finite energy resolution determined by both the detector and the electronic system. Qualitatively, the calculations well describe the experimental results. The algorithm that was developed determines the neutron dose equivalent, from the data of the 0.5μ chamber, to better than $\pm 20\%$ over the energy range of 30 keV to 14.5 MeV. The same algorithm also determines the dose equivalent from the data of the 2μ chamber to better than $\pm 20\%$ over the energy of 70 keV to 14.5 MeV.

The efficiency of the chambers is low and has an average value of 330 counts per mrem, or equivalently about 0.2 c/s per mrem/h. This efficiency enables the measurement of dose equivalent rates only above 100 mrem/h for an integration period of 3 seconds. However, integrated dose equivalents can be measured as low as 0.1 mrem.

I. INTRODUCTION

During the last few years there has been a growing interest in the development of small portable neutron dosimeters.⁽¹⁻⁵⁾ Real time dosimeters which are based on moderation of the incident neutrons are cumbersome, heavy and usually over-respond in the energy region of 1-100 keV and under-respond in the energy region above 9 MeV.

Tissue equivalent proportional chambers, usually of the Rossi spherical type,⁽⁶⁾ measure the energy deposited by recoil particles in an appropriate gas corresponding to small tissue volumes. They have been utilized in field measurements^(1,2,7,8,9) to determine dose equivalents. Equivalent tissue thicknesses of 1 and 2 μ have been used.^(1,2,8) In these studies the dose equivalent was found by using a functional relationship between the event size or lineal energy (energy deposited divided by an effective diameter of the chamber) and the LET (Linear Energy Transfer) of the recoiling particles. This method was determined to be improper,⁽¹⁰⁾ especially for low neutron energies. The main reason for this is that most of the recoil particles generated by low energy neutron interactions, are either stopped in the gas, or lose a large fraction of their energy when traversing the chamber. This contradicts the basic assumption made by Rossi^(6,11) that the energy loss of the recoil particles is negligible compared with their energy upon entering the gas.

Ricourt et al,⁽¹²⁾ and Stinchcomb and Borak⁽¹³⁾ suggested the use of an effective parameter, y' , instead of the conventional lineal energy parameter, y . The relation between the two was given by:

$$y' = \frac{8}{9} y \quad (1)$$

where y' was equated to the LET. Theoretical calculations were performed⁽¹³⁾ to verify this approach, but no experimental evidence was given for low neutron energies in the range of 10-300 keV. This energy region is especially important for determining the dose equivalent in nuclear power reactors.⁽¹⁴⁾

The differentiation method proposed by Rossi⁽¹¹⁾ has another disadvantage for use in portable instruments. This method requires good counting statistics. On the other hand, tissue equivalent chambers of low pressure and moderate size have relatively low sensitivity to neutrons.

In the present study we developed a simple theoretical algorithm for calculating the dose equivalent from the measured event size distribution in low pressure tissue equivalent chambers with effective tissue diameters between 0.5 and 2μ . Because the Rossi assumptions fail for low neutron energies and practical chamber size, the method used in this study does not correlate in a one-to-one correspondence between the lineal energy distribution and the LET of the recoil particles but rather divides the event size spectrum into two regions, and uses the total number of counts in these regions to extract the dose equivalent. This method does not suffer from statistical limitations beyond those that are determined by the detector efficiency.

The theoretical method developed, which took into account only neutron-hydrogen elastic interactions in the chamber wall and the gas, was tested experimentally using monoenergetic neutrons in the energy region of 10 keV to 14.5 MeV produced in the ${}^7\text{Li}(p,n){}^7\text{Be}$, $\text{D}(d,n){}^3\text{He}$ and $\text{T}(d,n){}^4\text{He}$ reactions, and several polyenergetic neutron sources. Polyenergetic sources included ${}^{252}\text{Cf}$ ($E_{\text{ave}} = 2.4$ MeV), ${}^{252}\text{Cf}$ moderated by a 30 cm diameter sphere of D_2O ($E_{\text{ave}} = 2.2$ MeV), ${}^{238}\text{Pu-F}$ ($E_{\text{ave}} = 1.1$ MeV), ${}^{238}\text{Pu-B}$ ($E_{\text{ave}} = 2.5$ MeV), and ${}^{238}\text{Pu-Be}$ ($E_{\text{ave}} = 4.5$ MeV), where E_{ave} is the dose equivalent-weighted average energy.

Section II describes the calculations performed to obtain the algorithm. In Section III the experimental studies are presented. The theoretical and experimental results are described in Section IV. Conclusions and summary are given in Section V.

II. THEORETICAL CONSIDERATIONS

The theoretical calculations in this study were carried out in the energy region of 10 keV to 14.5 MeV. The purpose of the calculations was to provide an algorithm for calculating the dose equivalent from the measured energy deposition of the recoil particles. In this energy region, the dose equivalent in tissue, contributed by charged particle recoils, originates mainly from elastic collisions of the incident neutrons with hydrogen atoms. Moreover, the number of events in the chamber is dominated by proton recoils. Therefore, the calculations performed considered only elastic scattering of the neutrons with hydrogen atoms in the wall and in the gas. A non-negligible fraction of the dose equivalent for neutron energies in the range of 10-50 keV results from gamma interactions that are produced by neutron capture collisions. In order to

measure this gamma contribution, the detector should be embedded inside a phantom. Our dosimeter measures the dose equivalent in free air and discriminates all gamma interactions in the detector. However the neutron fluence-to-dose equivalent conversion factors utilized in the present study include the contribution of gamma interactions in the body, therefore compensating for the discrimination of the gammas. The calculations were not aimed to be complete and most accurate, and simplifying assumptions were made in order to fit them onto a Hewlett Packard 9845B microcomputer. In spite of the simplifying assumptions, the calculations provide a guideline for a new algorithm which represents the dose equivalent.

The detectors considered were Rossi-type tissue equivalent chambers, with equivalent tissue diameters ranging between 0.5 and 2μ . Both the walls, which are made of Shonka material,⁽¹⁵⁾ and the tissue equivalent Rossi-type gas contain 10.3% hydrogen by mass (see Fig. 1).

It was assumed in the calculations that at each point in the wall the neutrons interact normal to the surface of the tissue equivalent chamber.

For neutron energies (E_n) less than 0.5 MeV, the total cross section, σ_{tot} , was parameterized in the following way:⁽¹⁶⁾

$$\sigma_{tot}(\text{barns}) = 3\pi/[1.206E_n + (-1.86 + 0.0842E_n + 0.00013E_n^2)^2] + \pi/[1.206E_n + (0.422 + 0.13E_n)^2]. \quad (2)$$

For neutron energies greater than or equal to 0.5 MeV, the total cross section was parameterized as follows:⁽¹⁷⁾

$$\sigma_{tot}(\text{barns}) = 4.83/\sqrt{E_n} - 0.578 \quad (3)$$

where in both equations (2) and (3) the neutron energy is given in MeV.

The differential cross section was assumed to be isotropic in the center-of-mass system, leading to the following relation in the laboratory system:

$$\frac{d\sigma}{d\Omega}(E_n) = \frac{\sigma_{tot}(E_n)}{\pi} \cdot \cos \Theta \quad (4)$$

where Θ is the proton scattering angle. The following assumptions were also made:

- Multiple scattering of recoil protons was neglected even when the track length was of the order of the proton range, i.e. the protons were assumed to move in straight lines in the wall and in the gas.
- Neutrons interact only once with the wall material or the gas, i.e. no multiple neutron interactions were considered.
- The path lengths of the recoil protons and the energies deposited in the gas were found using the continuous-slowing-down approximation, i.e. the range R for a given energy E_0 was determined by:

$$R_p(E_0) = \int_0^{E_0} dE / (dE/dx) \quad (5)$$

where dE/dx is the stopping power of the proton.

Under these assumptions, the number of recoil protons per unit area generated in the wall per incident neutron/cm², $N_p(E_n)$, is given by:

$$N_p(E_n) = 6.2 \times 10^{-5} \int_0^{R_{\max}(E_n)} \int_{\phi=0}^{2\pi} \int_{\Theta=0}^{\Theta_{\max}(t)} \exp[-6.2 \times 10^{-5} \sigma_{\text{tot}}(E_n)(T-t)] \frac{d\sigma}{d\Omega}(E_n) dt d\Omega \quad (6)$$

where $\Theta_{\max}(E_n)$ is the range of a proton with an energy E_n . The geometric notations of equation (6) are shown in Fig. 1. $\Theta_{\max}(0 \leq \Theta_{\max}(t) \leq \pi/2)$ depends on the point of interaction, $t(\text{mg/cm}^2)$, in the wall and is the maximum proton scattering angle beyond which protons do not reach the gas; $T(\text{mg/cm}^2)$ is the thickness of the wall. It was also assumed that the area seen by the incident neutrons was nearly R^2 , where R is the radius of the sphere.

A similar equation to (6) was used to derive the number of interactions in the gas, $N'_p(E_n)$, and is given as follows:

$$N'_p(E_n) = 6.2 \times 10^{-5} \exp[-6.2 \times 10^{-5} \sigma_{\text{tot}}(E_n) \cdot T] \int_0^{D_{\text{eff}}} \int_{\phi=0}^{2\pi} \int_{\Theta=0}^{\pi/2} \frac{d\sigma}{d\Omega}(E_n) dt d\Omega \quad (7)$$

TABLE 1

STOPPING POWER VALUES OF PROTONS IN TISSUE

<u>Proton Energy (keV)</u>	<u>dE/dx (keV/μm) (Ref. 18)</u>	<u>dE/dx (keV/μm) (Ref. 19)</u>
1	19.3	12.0
2	27.4	16.0
3	33.6	19.0
6	47.5	28.0
10	61.3	36.0
20	80.9	51.0
30	92.6	63.0
60	105.7	90.0
80	104.7	100.0
100	100.8	95.0
200	76.1	77.0
300	60.1	62.0

where D_{eff} (mg/cm^2) was determined from the area seen by the incident neutrons and by the mass of the gas.

It is clear from equation (6) that only part of the recoil protons generated in the wall reach the gas. The probability of reaching the gas depends on the point of interaction, $t(\text{mg}/\text{cm}^2)$, and on the initial proton energy E_p . This energy depends on the incident neutron energy, E_n , and the scattering angle θ in the following way:

$$E_p = E_n \cdot \cos^2 \theta. \quad (8)$$

The proton reaches the gas only if its range, R_p , is greater than $t/\cos \theta$. If the range R_p is greater than $t_1 = t/\cos \theta + D_{\text{eff}} \cos \theta$, the proton is not stopped in the gas and deposits an amount of energy corresponding to a proton range of $R_p - t_1$. The wall thickness, T , was divided into 100 equally spaced intervals, and the neutron was allowed to interact with equal probability in each of these intervals. The proton was also allowed to be scattered into any angle between θ and $\theta_{\text{max}}(t)$ with a probability given by the product $\sin \theta \cos R$ [see equations (4) and (6)]. A similar procedure was applied to interactions in the gas. However, any interaction in the gas leads to some energy deposition.

The calculations were performed for two sets of stopping power values of tissue. The first set was derived using stopping power values for H, C, N, and O given by Andersen and Ziegler,⁽¹⁸⁾ and the second set was that of Auxier et al.,⁽¹⁹⁾ with the Northcliffe and Schilling extrapolation⁽²⁰⁾ at low proton energies. The two sets nearly overlap beyond a proton energy of 200 keV as is evident in Table 1. However, at low proton energies, the dE/dx values given by Andersen and Ziegler are higher than those given by Auxier et al.

The energy deposited by the protons in the gas was found by a range-energy relation which was parameterized from the dE/dx values either of Andersen and Ziegler⁽¹⁸⁾ or of those used by Auxier et al.⁽¹⁹⁾ The parameterized relation with dE/dx values from Andersen and Ziegler is given as follows:

$$R_p(E_o)(\text{mg}/\text{cm}^2) = \begin{cases} 0.507 E_o^{0.587} & 0 \leq E \leq 0.1 \text{ MeV} \\ 0.093 + 2.09 E_o^{1.727} & E > 0.1 \text{ MeV} \end{cases} \quad (9)$$

The parameterized relation with dE/dx values from Auxier et al was given by:

$$R_p(E_o)(\text{mg}/\text{cm}^2) = \begin{cases} 0.548 E_o^{0.508} & 0 \leq E_o \leq 0.1 \text{ MeV} \\ 0.136 + 2.005 E_o^{1.767} & E_o > 0.1 \text{ MeV} \end{cases} \quad (10)$$

The energy deposited by a proton depends on its energy upon entering the chamber and on its trajectory length in the gas.

The protons were grouped in deposition energy bins of 1 keV width to form a distribution $F(E_p)$ and were divided into four categories similar to those suggested by Caswell.⁽¹⁰⁾ These include

- a. Protons generated in the wall that completely traverse the gas.
- b. Protons generated in the wall and stopped in the gas.
- c. Protons generated in the gas that escape the gas.
- d. Protons generated in the gas and stopped in it.

The program also calculated the total number of protons that deposit a significant amount of energy (> 1 keV) in the gas, and also the average track length of protons in the gas, D_{ave} , given as follows:

$$D_{ave} = \left(\sum_{i=1}^n p_i l_i \right) / N \quad (11)$$

where p_i is the probability that a proton deposits a significant energy in the gas, l_i is its track length, and N , the total number of protons depositing some energy in the gas, is given by:

$$N = \sum_{i=1}^n p_i \quad (12)$$

The distribution of protons as a function of the deposited energy in the gas, $F(E_p)$, was folded with the energy resolution of the detector and the electronic system. The energy resolution can be expressed as follows:

$$W^2 = W_N^2 + W_M^2 + W_e^2 \quad (13)$$

where W represents the full width at half maximum (FWHM), W_N is the contribution from the statistical nature of the formation of ion pairs in the gas, W_M is the contribution from the gas multiplication process, and W_e is the contribution from electronic noise. The tissue equivalent chambers have an internal ^{244}Cm alpha source. It was difficult to estimate the energy resolution from this source, because there is some broadening caused by the source finite thickness. To account for the energy dependence of detector resolution, equation (13) was written as:

$$W^2 = W_e^2 + a(E_p) \quad (14)$$

where E_p is the proton deposition energy in the gas. W_e was estimated to be 3 keV, and the function $a(E_p)$, derived from studies of Byrne, ^(21,22) was given by:

$$a(E_p) = 0.028E_p + 1.6, \quad (15)$$

where E_p is in keV. Equation (14) leads to a FWHM of about 33% and 6% at proton energy depositions of 10 keV and 60 keV respectively.

The detector response $G(E_p, E_p')$ was parameterized in terms of a normalized Gaussian in the form

$$G(E_p, E_p') = \frac{1}{\sqrt{2\pi} \sigma} \exp - \left[\frac{(E_p - E_p')^2}{2\sigma^2} \right], \quad (16)$$

and the observed response $f(E_p')$ was given by:

$$f(E_p') = \int_0^{E_p^{\max}} F(E_p) G(E_p, E_p') dE_p \quad (17)$$

where $E_p^{\max}$ is the maximum deposited energy in each detector. The distribution

$f(E_p')$ was then converted into the distribution in linear energy $f(y_p')$ where $y_p' = E_p'/D$ and D is the diameter of the chamber.

To summarize, the outcome of the calculations includes the following:

- a. The proton energy deposition distribution, $F(E_p)$.
- b. The broadened energy deposition distribution, $f(E_p')$.
- c. The broadened energy distribution as a function of the lineal energy, $f(y_p')$.
- d. The distribution of the initial stopping powers for the protons entering the gas or generated in the gas.
- e. The distribution of track lengths of the protons that deposit a significant amount of energy in the gas.
- f. The total number of protons per unit of dose equivalent.
- g. The total number of protons generated in the wall that deposit a significant amount of energy in the gas.
- h. The total number of protons generated in the wall and stopped in the gas.
- i. The total number of protons generated in the gas.
- j. The total number of protons generated in the gas and stopped in it.

III. EXPERIMENTAL CONSIDERATIONS

A. Detectors

Two spherical tissue equivalent detectors, manufactured by Far West Technology (Goleta, CA), were irradiated simultaneously. The detectors were of Rossi type with a diameter of 5.7 cm. They were filled with a Rossi type gas composition.⁽¹¹⁾ The gas comprised H, C, O, and N in mass percentages of 10.2, 45.6, 40.7, and 3.5 respectively. This mixture has a somewhat different composition in carbon and oxygen than muscle tissue,⁽¹⁵⁾ but the differences are insignificant for the purpose of this study. The chambers were contained in an aluminum can, 1.6 cm thick, which served as a vacuum tight container. The walls were made of Shonka A-150 material, 3.2 mm thick. Each detector contained a magnetically operated ^{244}Cm alpha particle source with an energy of 5.8 MeV. This source was used to calibrate the gain of the chamber and the electronic system.

Pressures of 6.4 and 25.6 mm Hg were used to simulate tissue thicknesses of 0.5 and 2μ respectively. The gas density is $1.04 \times 10^{-3} \text{ g/cm}^3$ (at 20°C and 1 atm).

The characteristic energy loss, dE/dx , for 5.8 MeV alpha particles in a Rossi type gas has two different values in the literature. Northcliffe and Schilling⁽²⁰⁾ published a value of 0.91 MeV/mg/cm^2 , whereas Andersen and Ziegler⁽²³⁾ published a value of 0.83 MeV/mg/cm^2 . For this study we adopted a value of 0.91 MeV/mg/cm^2 . The uncertainty in this choice does not affect the major conclusions of the present study.

The 0.5 and 2μ detectors were operated at voltages of 550 and 700 V respectively. The grids were operated at about 80% of the anode voltage. Each detector was coupled to a Canberra 2003B preamplifier whose output was connected to an Ortec 572 shaping amplifier. The overall gain of the two detection systems was identical, and the ^{244}Cm alpha pulse height was about 3.5 volts.

B. Irradiations with Monoenergetic Neutrons in the Energy Range of 10 keV to 1 MeV Using the $^7\text{Li}(p,n)^7\text{Be}$ Reaction

Monoenergetic neutrons in the range of 10 keV to 1 MeV were produced using a 3 MV Van-de-Graaff accelerator and the $^7\text{Li}(p,n)^7\text{Be}$ reaction. Proton energies varied between 1.95 and 2.8 MeV. The target consisted of 100 g/cm^2 of lithium evaporated onto a 0.5 mm thick tungsten disk. The other materials between the target and the detectors were 1-2 mm of stainless steel and a Freon cooling jacket. The beam tube was 5 cm in diameter with stainless steel walls, 4 mm thick. Both the tungsten backing and the surrounding stainless steel material caused some scattering of neutrons at low energies. This scattering effect for neutron energies 10-50 keV is later discussed in the paper. The experimental configuration is shown in Fig. 2.

The main fluence calibration was achieved by using a long counter developed by East and Walton.⁽²⁴⁾ The long counter is a polyethylene cylinder, 22.9 cm long and 22.9 cm in diameter. A single ^3He proportional detector, pressurized to 6 atm was embedded along the symmetry axis of the cylinder. The absolute efficiency of this detector was measured by Evans.⁽²⁵⁾ Although Evans found an intrinsic efficiency peaking slightly at 450 keV neutron energy, we used an energy averaged efficiency constant over the entire energy range. The efficiency adopted was 10% lower than the value measured for the ^{252}Cf source.

Using an NBS calibrated ^{252}Cf source whose strength was 2.1×10^5 n/sec, the absolute efficiency for this source was (0.020 ± 0.002) and the effective center was 8 cm from the front surface. Because the long counter was positioned at 350 cm from the target, the effective center was considered constant over the neutron energy range of 100 keV to 1.2 MeV. During the experiments, the integrated beam current was also recorded and served as an additional calibration whenever the proton energy remained constant.

A Shalev type $^{(26,27)}\text{}^3\text{He}$ spectrometer was also used for energy calibration. This detector is a cylindrical gridded ionization chamber, 15 cm long and 5 cm in diameter. The chamber is pressurized with a mixture of helium-3, argon, and methane at 4.2 atm. Its resolution was 30 keV for 1 MeV neutrons and 16 keV for thermal neutrons. The ^3He spectrometer was positioned at a distance of 120 cm and at 45° .

An Eberline NRD-1 9" sphere rem meter was used for relative dose equivalent measurements. The calibration of the NRD-1 varies with the neutron energy. The efficiency expressed as counts per mrem at 100 keV is greater by a factor of 3 than it is at 1 MeV neutron energy. Therefore, for several irradiations when the proton energy changed, the NRD-1 was positioned at appropriate angles to keep the neutron energy incident at the detector constant. For neutron energies greater than 600 keV, the NRD-1 was used as a complementary measure of the absolute dose equivalent. It was positioned at 120 cm from the target at various angles with respect to the incident beam direction.

The 0.5 and 2μ tissue equivalent chambers were positioned at the same angle, but at opposite sides with respect to the beam direction. During the experiments, angles were varied between 20° and 110° .

Neutron energy resolution in the $^7\text{Li}(p,n)^7\text{Be}$ reaction was determined mainly by two factors:

- 1) proton energy loss in the target and
- 2) the solid angle of the detectors.

The maximum energy loss of the proton in the target was about 12 keV and 10 keV for proton energies of 2 MeV and 2.8 MeV respectively. Because the interaction probability is the same irrespective of the point of interaction in the target, the neutron energy at an angle θ has values between $E_n(\theta, E_p)$ and $E_n(\theta, E_p - \Delta E_p)$ where ΔE_p is the maximum energy loss in the target.

The angle covered by the tissue equivalent chambers at the closest distance of 40 cm was 8° . The angle covered by the long counter was 3.6° and the angles

covered by the NRD-1 and ^3He spectrometer were 11° and 7° respectively. Therefore, the energy spread of neutrons incident on a detector positioned at an angle Θ is between $E_n(\Theta + \Delta\Theta/2, E_p - \Delta E_p)$ and $E_n(\Theta - \Delta\Theta/2, E_p)$, where $\Delta\Theta$ is the angle covered by the detector. For given values of ΔE_p and $\Delta\Theta$, the energy broadening is determined by the reaction kinematics.

At proton energies higher than 2.5 MeV, neutrons are also produced by the $^7\text{Li}(p,n)^7\text{Be}^*$ reaction, where the $^7\text{Be}^*$ nucleus is in its first excited state (0.43 MeV). The cross section for this reaction increases with the increase in proton energy. At 2.8 MeV and a neutron scattering angle of 20° , the ratio between the first excited and ground state transition cross sections is 12%.⁽²⁸⁾ Therefore, neutron energies between 600 keV and 1000 keV produced by proton energies higher than 2.5 MeV were contaminated by lower energy neutrons to an extent not greater than 12%. Their contribution was taken into account.

C. Interference of Scattered Neutrons in the $^7\text{Li}(p,n)^7\text{Be}$ Reaction

The interference of scattered neutrons with direct neutrons has been investigated. There were three reasons for scattered neutrons:

- 1) Scattering of neutrons from the floor.
- 2) Scattering of neutrons from the material surrounding the target, such as the tungsten backing, the cooling jacket, and the stainless steel vacuum pipe.
- 3) Neutrons generated by reactions of protons with other materials which might be present in the collimating slits, such as Cr, V, and Mn.

In order to estimate the scattering of neutrons from the floor, a comparison was made in three different configurations. First, the chambers were completely unmasked, second they were masked with polyethylene and cadmium, except for the target direction, and third they were masked only toward the target. The proton energy was 1.95 MeV and the chambers were mounted at 110° .

In order to estimate the number of neutrons that are produced prior to the interaction of the protons with the lithium target, we replaced the target with tungsten and measured the neutron yield with the long counter.

Furthermore, in order to estimate the number of scattered neutrons from the material surrounding the target, we positioned the tissue equivalent chambers at back angles where scattering of direct neutrons is kinematically forbidden. The proton energy was 1.91 MeV and the angle was 150° .

D. Neutron Fluence and Dose Equivalent Rates in the ${}^7\text{Li}(p,n){}^7\text{Be}$ Reaction

The average proton current for all experiments was 20 μA and the average neutron flux emerging from the target was 3×10^8 n/sec. Dose equivalent rates at the position of the tissue equivalent chambers varied between 150 and 1600 mrem/h.

Neutron fluences impinging the tissue equivalent chambers, the NRD-1, and the ${}^3\text{He}$ spectrometer were determined from the readings of the long counter and the differential cross section of the ${}^7\text{Li}(p,n){}^7\text{Be}$ cross section.⁽²⁸⁾ The fluence F , measured by the long counter, is given by:

$$F(\text{n/cm}^2) = N/(\epsilon \cdot S) \quad (18)$$

where N is the total counts detected by the long counter, ϵ is the intrinsic efficiency of the long counter, and S is its effective surface area. The value of S was 412 cm^2 . The fluence at an angle θ and distance d from the target, $F_{\theta,d}$, is related to F in the following way:

$$F_{\theta,d}(\text{n/cm}^2) = F \cdot \frac{d_{lc}^2}{d^2} \cdot \frac{\frac{d\sigma}{d\Omega}({}^7\text{Be} + {}^7\text{Be}^*, \theta)}{\frac{d\sigma}{d\Omega}({}^7\text{Be} + {}^7\text{Be}^*, 45^\circ)} \quad (19)$$

where d_{lc} is the distance from the target to the long counter, and

$$\frac{d\sigma}{d\Omega}({}^7\text{Be} + {}^7\text{Be}^*, \theta) = \frac{d\sigma}{d\Omega}({}^7\text{Li}(p,n){}^7\text{Be}) + \frac{d\sigma}{d\Omega}({}^7\text{Li}(p,n){}^7\text{Be}^*), \quad (20)$$

with cross sections in the laboratory system. The effect of the ${}^7\text{Li}(p,n){}^7\text{Be}^*$ reaction, which is significant only at proton energies above 2.5 MeV, was to decrease the average energy of the neutron. However, this decrease was usually small.

E. Monoenergetic Neutrons Using the $D(d,n)^3\text{He}$ and $T(d,n)^4\text{He}$ Reactions

The reactions $D(d,n)^3\text{He}$ and $T(d,n)^4\text{He}$ were carried out with a Kaman A-1001 neutron generator. The deuteron energy was 150 keV. The targets were of the form TiD_x and TiT_x where $x \approx 2$, and their thicknesses were about 0.59 mg/cm^2 . The neutron yields in the $D(d,n)^3\text{He}$ and $T(d,n)^4\text{He}$ reactions were about 10^8 and 10^{10} n/sec respectively. The target was mounted at 120 cm from the floor.

The experimental configuration for the $D(d,n)^3\text{He}$ reaction is shown in Fig. 3. The absolute calibration of the fluence at the position of the tissue equivalent chambers was achieved by the long counter,⁽²⁵⁾ positioned at 30° with respect to the beam direction and at a distance of 308 cm from the target. An Eberline NRD-1 rem meter was positioned at 45° and at a distance of 100 cm. This instrument was calibrated with a ^{252}Cf source to yield 3000 counts per mrem. The tissue equivalent chambers were positioned at three different angles, 10° , 88° and 135° , in order to obtain their average response in the region between 2 and 3 MeV.

Differential cross sections were obtained from the report by Liskien and Paulsen.⁽²⁹⁾ Because of large energy losses of the deuteron in the target, average neutron energies and cross sections were derived as will be discussed below.

The experimental setup for the $T(d,n)^4\text{He}$ reaction is given in Fig. 4. Because of high fluxes and space limitations, the absolute fluence determination was achieved primarily by utilizing two activation foils ^{63}Cu and ^{27}Al . The copper foil, with 69.1% ^{63}Cu and 30.9% ^{65}Cu , was covered with cadmium in order to avoid scattered thermal neutron activation. Fast neutrons interact with copper and aluminum as follows:

- 1) $^{63}\text{Cu} (n, 2n) ^{62}\text{Cu}$
- 2) $^{65}\text{Cu} (n, 2n) ^{64}\text{Cu}$
- 3) $^{27}\text{Al} (n, \alpha) ^{24}\text{Na}$

^{62}Cu and ^{64}Cu are positron emitters with half lives of 9.76 min and 12.8 h, respectively. ^{24}Na is a gamma emitter with gamma energies at 1.37 MeV and 2.75 MeV. The copper and aluminum foils were irradiated simultaneously at 15° and at 25 cm from the target. The aluminum disk, 2.38 g, was sandwiched between four copper foils, 650 mg each. Two of them were in front of the aluminum and two in the back.

Because 1) the abundance of ^{65}Cu is about half that of ^{63}Cu , 2) the half life of ^{64}Cu is about 80 times longer than that of ^{62}Cu , 3) the $^{65}\text{Cu}(n,2n)^{64}\text{Cu}$ cross section is larger by about a factor of 1.7 than that of $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ and, 4) the 511 keV abundance for ^{62}Cu is greater by a factor of 5.5 than that of ^{64}Cu , the activity of the copper foil at short periods after irradiation is dominated by the activity of ^{62}Cu .

The annihilation of positrons from ^{62}Cu was achieved by inserting the copper foils between two aluminum layers, each 4.5 mm thick, or alternatively by inserting them between two lead layers, each 1.2 mm thick. This amount of material was necessary to obtain the complete annihilation of positron energies up to 2.9 MeV. The copper activity was determined with two Ge(Li) detectors within a period of up to 30 minutes after irradiation. These detectors were calibrated with point gamma sources while aluminum or lead layers were positioned between the source and detector. It should be emphasized that the copper foils covered with annihilator material are extended 511 keV gamma ray sources and not point sources. The effect of the source size was checked by moving the foils to larger distances from the detector. The size effect was taken into consideration in all calculations.

The ^{24}Na activity was also measured with a Ge(Li) detector, by positioning the aluminum foils between 3 and 4 cm from the detector. Activation was determined by counting both peaks of ^{24}Na at 1.27 and 2.74 MeV.

Very good agreement was obtained between the fluxes derived from the copper and aluminum activation measurements.

F. The Determination of the Energy Loss of the Deuteron in the TiD_2 and TiT_2 Targets and of the Average Cross Sections

When the deuterons pass through TiD_2 or TiT_2 targets, they lose energy by coulombic interactions, thus the deuteron energy spectrum is effectively broadened. Because the differential cross section for both $\text{D}(d,n)^3\text{He}$ and $\text{T}(d,n)^4\text{He}$ reactions varies with the deuteron energy, it was necessary to extract the average deuteron energy and the average neutron energy at scattering angles of interest. Calculations were performed in order to find these quantities. The deuteron was traced along its path in the target, and for constant increments of energy loss, ΔE_i , the corresponding path length ΔR_i was recorded. The energy of the deuteron at a depth t in the target, after n intervals, is

$E_d - n\Delta E_i$. The number of deuterium or tritium atoms seen by the incident deuteron in each interval is proportional to ΔR_i . The average differential cross

section, $\left[\frac{d\sigma(\theta_n)}{d\Omega} \right]_{ave}$, for scattering angle θ_n is therefore given by:

$$\left[\frac{d\sigma(\theta_n)}{d\Omega} \right]_{ave} = \frac{\sum_{i=1}^N \left[\frac{d\sigma}{d\Omega}(\theta_n, E_d - i\Delta E_i) \right] \Delta R_i}{R_{max}} \quad (21)$$

where $(\theta_n, E_d - i\Delta E_i)$ is the laboratory differential cross section⁽²⁹⁾ for scattering angle θ_n , deuteron energy $(E_d - i\Delta E_i)$, and R_{max} is the total path length of the deuteron in the target.

The average energy of the deuteron $(E_d)_{ave}$ was determined in a similar way:

$$(E_d)_{ave} = \frac{\sum_{i=1}^N \sigma_{tot}(E_d - i\Delta E_i) \cdot \Delta R_i \cdot (E_d - i\Delta E_i)}{N \sum_{i=1}^N \sigma_{tot}(E_d - i\Delta E_i) \cdot \Delta R_i} \quad (22)$$

where $\sigma_{tot}(E_d - i\Delta E_i)$ is the total cross section for either the $D(d,n)^3\text{He}$ or the $T(d,n)^4\text{He}$ reactions for deuteron energy $(E_d - i\Delta E_i)$.

The energy loss of the deuteron in the TiD_2 and the TiT_2 targets was calculated using dE/dx values of Andersen and Ziegler,⁽²³⁾ assuming that the stopping power is the same for protons and deuterons with equal velocities. The ranges of the deuteron were parameterized in the form of $R = a E^C$ and are given in equations (23) and (24) for the TiD_2 and TiT_2 targets respectively.

$$R(\text{mg/cm}^2) = 0.027 E_d^{0.597} \quad (23)$$

$$R(\text{mg/cm}^2) = 0.026 E_d^{0.597} \quad (24)$$

E_d is the deuteron energy in keV.

The average deuteron energy and the average neutron energy for different scattering angles are given in Table 2.

TABLE 2

AVERAGE NEUTRON ENERGY (MeV)

Reaction	Average Deuteron Energy (keV)	Scattering Angle						
		<u>10°</u>	<u>30°</u>	<u>45°</u>	<u>88°</u>	<u>135°</u>	<u>15°</u>	<u>30°</u>
D(d,n) ³ He	110	2.86	2.81	2.76	2.48	2.24		
T(d,n) ⁴ He	97						14.75	14.6

Differences shown in the average deuteron energy between the two reactions are caused by differences in the behavior of the total cross section for the two reactions as a function of the deuteron energy.

The average differential cross sections, used for D(d,n)³He, are given in Table 3.

TABLE 3

AVERAGE $\frac{d\sigma}{d\Omega}$ (θ) (mb/sr) IN THE LABORATORY SYSTEM

Reaction	Scattering Angle				
	<u>10°</u>	<u>30°</u>	<u>45°</u>	<u>88°</u>	<u>135°</u>
D(d,n) ³ He	1.37	1.18	0.977	0.632	0.850

Because the cross sections for ⁶³Cu(n,2n)⁶²Cu and ²⁷Al(n, α)²⁴Na depend on the neutron energy, the average cross sections at 15° neutron scattering angle were found in a similar way as the average cross section for the D(d,n)³He and

$T(d,n)^4\text{He}$ reactions. The path lengths were folded with the neutron energies and the $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ and $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ total cross sections. The cross section for these reactions as a function of the neutron energy were from ENDF-B IV.⁽³⁰⁾ The average cross sections at 15° were 583 mb and 116 mb for the $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ and $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ reactions respectively.

These cross sections, together with the differential cross sections given by Liskien and Paulsen⁽²⁹⁾ and the activity measured, yielded the fluence at the position of the tissue equivalent chambers. For the $D(d,n)^3\text{He}$ reaction, the fluences at the position of the tissue equivalent chambers or the NRD-1 rem meter were derived using the average cross sections shown in Table 3 and the readings of the long counter.

G. Polyenergetic Neutron Sources

The tissue equivalent chambers were also irradiated with polyenergetic neutron sources. These sources and their dose equivalent-weighted average energies included bare ^{252}Cf ($E_{\text{ave}} = 2.49$ MeV), ^{252}Cf moderated by a D_2O sphere, 30 cm in diameter,^(31,32,33) ($E_{\text{ave}} = 2.2$ MeV), $^{238}\text{Pu-F}$ ($E_{\text{ave}} = 1.1$ MeV),^(34,35) $^{238}\text{Pu-B}$ ($E_{\text{ave}} = 2.5$ MeV),^(34,35) and $^{238}\text{Pu-Be}$ ($E_{\text{ave}} = 4.5$ MeV). The yields of these sources were determined using a long counter⁽²⁵⁾ positioned at several distances from the sources. The yields are summarized in Table 4.

TABLE 4

POLYENERGETIC NEUTRON SOURCES

Source	E_{ave} (MeV)	Yields (n/sec)
$^{238}\text{Pu-F}$	1.1	8.57×10^6
$^{238}\text{Pu-B}$	2.5	1.78×10^7
$^{238}\text{Pu-Be}$	4.5	9.61×10^6
^{252}Cf	2.4	5.66×10^7

The 0.5 and 2 μ chambers were irradiated simultaneously with these sources at a distance of 100 cm.

H. Extraction of Dose Equivalents From the Measured Fluences

A discrepancy exists at several neutron energies in the values of the fluence-to-dose equivalent conversion factors between ICRP-21 (Ref. 36) and NCRP-38 (Ref. 37).

In this study we followed the recommendations of Cross and Ing⁽³⁸⁾ and used the values given in ICRP-21 in the region of 1 keV to 10 MeV whereas the value at 14.5 MeV was taken from NCRP-38. The fluence-to-dose equivalent conversion factors at energies not listed in ICRP-21 were found using a linear interpolation on a $\log E_i$, $\log F_i$ plot, where E_i and F_i are the neutron energies and conversion factors of ICRP-21. The conversion factors refer to irradiations by a unidirectional broad beam of neutrons at normal incidence and are evaluated at the depth of maximum dose equivalent. The values used in this study are listed in Table 5.

The conversion factors for ^{252}Cf and D_2O -moderated ^{252}Cf were from references (33) and (39), and those of $^{238}\text{Pu-F}$, $^{238}\text{Pu-B}$, and $^{238}\text{Pu-Be}$ were found by folding the conversion factors in Table 5 with spectra published in references (33) and (34).

In the reaction $^7\text{Li}(p,n)^7\text{Be}$, above proton energies of 2.5 MeV, the fluence to dose equivalent conversion factors were found using the following relation:

$$\bar{f} = b \cdot f + (1-b)f^* \quad (25)$$

where f and f^* are the conversion factors for neutron energies generated in the $^7\text{Li}(p,n)^7\text{Be}$ (ground state) and $^7\text{Li}(p,n)^7\text{Be}^*$ (0.431 MeV) reactions respectively, and b is the fraction of neutrons produced in the $^7\text{Li}(p,n)^7\text{Be}$ (ground state) reaction.

TABLE 5

FLUENCE-TO-DOSE EQUIVALENT CONVERSION FACTORS

Average Neutron Energy (keV) of Source	Factor 10^{-9} Rem/n/cm ²
7 .5	0.992
12	1.08
21	1.73
44	3.06
69	4.35
93	5.47
143	7.61
194	9.61
246	11.5
296	13.3
395	16.5
495	19.7
595	22.6
701	25.3
801	27.3
899	30.2
1012	32.7
2500	40.3
14600	57.9
²⁵² Cf	33.2
²⁵² Cf + D ₂ O	9.0
²³⁸ Pu-f	33.1
²³⁸ Pu-B	37.0
²³⁸ Pu-Be	39.7

IV. RESULTS AND DISCUSSION

A. Theoretical Results

The primary objective of the theoretical calculations was to obtain a simple algorithm for deriving the dose equivalent from the spectra measured by low pressure tissue equivalent chambers, especially at low neutron energies (10-300 keV). Although these calculations included several simplifying assumptions, they served as a guideline for obtaining the algorithm and for interpreting the experimental results. Even though the calculations provide a qualitative picture, they are nonetheless compared to the experimental results.

The first outcome of the calculations was a comparison between the proton recoil spectra of the 0.5 and 2μ tissue equivalent chambers. Figures 5 and 6 show the calculated spectra as a function of the lineal energy for the two chambers and for several energies in the range of 8 keV to 69 keV. The calculations use stopping powers of Andersen and Ziegler.⁽¹⁸⁾ As expected the end point of each spectrum increases with incident neutron energy, but both the end point and the shape for a certain energy are vastly different between the two chambers. A similar situation occurs at 93 keV neutron energy (Fig. 7).

The curves in Fig. 7 are normalized to the same number of incident neutrons. It can be seen that no similarity exists between the energy deposition spectra in the two chambers. The maximum lineal energy for the 0.5μ chamber is almost double that of the 2μ chamber. The spectra, especially for the 2μ chamber, do not reflect the LET of the recoiling protons. For neutron energies between 10 and 100 keV, a large fraction of the events have apparent lineal energy values below 10 keV/ μ , whereas in reality only a small fraction of the protons have LET values in this region. The ratio of the number of protons with apparent lineal energies in the region below 10 keV/ μ to the total number of protons depositing a significant amount of energy in the gas is shown in Fig. 8 for neutron energies between 10 and 300 keV. The spectra for neutron energies below 100 keV, and especially for the 2μ chamber, reflect primarily those protons generated in the wall and stopped in the gas, or recoil protons generated in the gas that lose a great fraction of their initial energy before escaping the gas. At higher neutron energies the spectra in the two chambers are similar as is shown in Figure 9 for a neutron energy of 1 MeV. At this energy the spectra in the two chambers are similar.

In order to show the inappropriateness of using the 2μ chamber as an LET chamber for neutron energies below 300 keV, we compared the 0.5 and 2μ in three different ways which represent the following Rossi assumptions, which are necessary and sufficient for using a tissue equivalent chamber as an LET detector:

- 1) The particles are generated only in the wall of the chamber.
- 2) The stopping power of the recoiled particles does not change significantly when the particles traverse the chamber; that is, the ranges of the particles are much longer than the diameter of the chamber.
- 3) The mean track length of the recoiled particles does not depend on the neutron energy, thus a lineal energy can be defined by dividing the energy deposited by an average diameter of the chamber. This diameter is independent of the neutron energy.

Figure 10 shows the calculated ratio between the number of protons generated in the wall and stopped in the gas, to the total number of protons generated in the wall that deposit a significant amount of energy in the gas. The calculations were carried out for two sets of dE/dx values, adopted by Andersen and Ziegler⁽¹⁸⁾ or by Auxier et al.⁽¹⁹⁾ The calculations with both sets show that for 100 keV incident neutron, about 25% and 100% of the protons generated in the wall in the 0.5 and 2μ chambers, respectively, are stopped in the gas. Also, quite a large percentage of the protons generated for neutron energies up to 300 keV lose a substantial fraction of their initial energy in the gas for the 2μ chamber. Because the dE/dx values of Auxier et al are lower than those of Andersen and Ziegler for proton energies below 100 keV, the number of stopped protons is somewhat smaller using the first set of dE/dx values, but is still appreciable.

Figure 11 shows the ratio between the number of protons generated in the gas and the total number of protons generated in either the wall or the gas that deposit a significant amount of energy in the gas. For a neutron energy of 100 keV, the fraction of protons generated in the gas is about 35% and 65% for the 0.5 and 2μ chambers respectively, and for a neutron energy of 300 keV this fraction is about 20% and 50% for the 0.5 and 2μ chambers respectively. This fraction is somewhat smaller using the dE/dx values of Auxier et al, because more particles are predicted to enter the chamber from the wall, whereas the

total number of protons generated in the gas is clearly independent of the set of stopping powers used.

Figure 12 displays the track length in the gas averaged over all protons, including those generated in the wall or in the gas (see equation 13), compared to the maximum average track length. It is seen that the average track length increases with the incident energy. At 100 keV, this average diameter is about 70% and 40% of the maximum for the 0.5 and 2μ chambers respectively. For a neutron energy of 300 keV, the ratio is still 60% for the 2μ chamber. Using the dE/dx values of Auxier et al, the ratio is somewhat increased, because the track lengths for the low energy protons increase. These data indicate that the definition of lineal energy in terms of the energy deposited divided by an average diameter is not appropriate at low neutron energies.

The above results indicate that the correspondence between lineal energy, measured in both the 0.5 and the 2μ chambers, and the LET of the recoiling protons in the gas is not straightforward for neutron energies below 300 keV. The extraction of the LET spectra from the lineal energy spectra must involve complicated calculations and unfolding procedures.⁽¹⁰⁾

The approach adopted in the present study was to correlate the experimental data to the dose equivalent in terms of macroscopic parameters, rather than microscopic (such as the linear energy transfer). This correlation should be simple and not limited by statistical considerations beyond the intrinsic efficiency of the chambers. The approach was to correlate the total number of recoil protons which deposit a significant amount of energy in the chambers to the dose equivalent.

Figures 13 and 14 show the calculated total number of protons per mrem of incident neutrons, which deposit an energy above 10 keV/ μ for the 0.5 and 2μ chambers respectively. The cutoff at 10 keV/ μ was chosen since such a cutoff is necessary in field situations to avoid interference from photon interactions. It is observed that the total number of protons per mrem of neutrons oscillates around an average number of about 300 for both the 0.5 and 2μ chambers. At low energies the total number of particles decreases more rapidly in the 2μ chamber as compared to that in the 0.5 μ chamber, despite the fact that the total number of recoils is much larger for the 2μ chamber. The reason is that a substantial fraction of the recoil protons for low energy neutrons occur below 10 keV/ μ for the 2μ chamber.

The total number of protons in the two chambers shows some ambiguity between neutron energies below 100 keV and energies above 3 MeV. A maximum is present in both these energy regions. The reason for this is as follows: At low energies, the elastic cross section is large and a large fraction of the particles are generated in the gas. Also, the fluence per unit dose equivalent is high. At high neutron energies, although the elastic cross section is small and the fluence-to-dose equivalent is relatively small, the average proton energy is large and the effective thickness of the wall from which protons can reach the gas is large. It is also seen in Figs. 13 and 14 that for both chambers, the total number of recoil protons has a minimum around a neutron energy of 500 keV.

Because the total number of protons per mrem oscillates as a function of the neutron energy, some spectroscopic information should be extracted from the spectrum of the deposited energy in order to correct for this oscillatory behavior. This spectroscopic information should decrease the contribution of the number of recoil protons in the energy region below 100 keV and above 1.5 MeV, and at the same time increase the contribution of the number of recoil protons in the region between 100 keV and 1.5 MeV.

The spectroscopic information that was extracted is displayed in Figs. 15 and 16. These figures show the fraction of recoil protons in the region 10-30 keV/ μ compared to the total number of protons above 10 keV/ μ , for the 0.5 and 2 μ chambers. It is seen that for both chambers, the above-mentioned fraction shows a maximum at low and high neutron energies, while a minimum occurs near 500 keV. It is obvious that the fraction of recoil protons in the region >30 keV/ μ compared to the total number of protons must show a minimum in the low and high neutron energy regions and a maximum near 500 keV. The calculated fraction above 30 keV/ μ is shown in Fig. 17 for the 0.5 μ chamber.

Therefore, instead of taking the total number of particles, the dose equivalent can be represented as a linear combination of the number of particles in two regions: a) (10-30) keV/ μ and b) 930-120) keV/ μ , as follows:

$$DE(\text{mrem}) = \frac{aN (10 - 30 \text{ keV}/\mu) + bN (30 - 120 \text{ keV}/\mu)}{330} \quad (26)$$

Parameter a should be much smaller than b, in order to decrease the contribution

for the low and high neutron energies and increase the contribution in the region between 100 keV and 1.5 MeV. Equation 26 will not describe the dose equivalent accurately at low neutron energies below 75 keV for the 2μ chamber, because a great fraction of the recoil protons are below the cutoff energy of 10 keV/ μ .

The extraction of the dose equivalent using equation 26 is very simple and can be easily programmed into a microprocessor-based instrument. It does not suffer from any statistical limitation beyond the intrinsic efficiencies of the chambers.

B. Experimental Results

Figures 18-21 show a comparison between the 0.5 and the 2μ chambers for several incident neutron energies. The overall gains (per keV/ μ) and the dose equivalents are the same for both chambers. It can be seen that the experiments follow qualitatively the shapes of the spectra and differences predicted theoretically by taking into account only elastic scattering with hydrogen atoms. A dramatic difference is shown between the two chambers at 44 keV (Fig. 18), but the difference is also noticeable at a neutron energy of 300 keV (Fig. 20). The two chambers yield nearly the same spectra at a neutron energy of 900 keV (Fig. 21). It should be noted that the 44 keV spectra include a scattering component. By subtracting this component, the difference between the two chambers is largely magnified.

Table 6 compares several spectra ≥ 300 keV for the 0.5 μ chamber. The comparison shows the fraction of particles, in 10 keV/ μ bins, for 300 keV, ^{252}Cf , and $^{238}\text{Pu-Be}$ sources and also for 14.6 MeV. The trend is clear. The higher the incident neutron energy, the less the energy deposited by the protons in the gas, a result expected from the stopping power values of the recoil particles.

TABLE 6*

FRACTION OF ENERGY DEPOSITED AS A FUNCTION OF LINEAL ENERGY FOR THE 0.5 μ CHAMBER

keV/ μ	300 KeV	²⁵² Cf	²³⁸ Pu-Be	14.6 MeV
10-20	16.9	43.5	57.7	65.0
20-30	14.3	22.5	20.5	16.6
30-40	12.5	12.3	8.9	6.8
40-50	11.9	7.4	4.8	3.8
50-60	11.1	4.8	2.7	2.4
60-70	10.5	3.3	2.0	1.8
70-80	9.6	2.4	1.4	1.3
80-90	7.9	1.8	1.2	1.0
90-100	4.5	1.3	0.5	0.6
100-110	0.9	0.6	0.2	0.3
110-120	0.	0.1	0.1	0.3

*Numbers are given as percentages of total events above 10 keV/ μ .

The interference of scattered neutrons with the direct neutrons was observed at neutron energies between 10 and 50 keV. The presence of scattered neutrons was most pronounced when the chambers were positioned at backward angles, such as 110°. At 15 keV, for instance, the neutron yield in the 2 μ chamber was observed above 15 keV/ μ (see Fig. 23), an obvious anomaly by energy conservation considerations.

The yields and spectra obtained in the chambers were similar when the chambers were completely unmasked and when they were masked from all directions except the direction of the target. When the target direction was masked, only negligible neutron yield was obtained. These experiments lead to the conclusion that the scattering of neutrons originated from the target surroundings.

When replacing the lithium target with tungsten, no neutron yield was observed in either the tissue equivalent chamber or the long counter. This means that no neutrons are produced before the protons interact with the lithium target.

When positioning the chambers at backward angles, for which scattering of neutrons is kinematically forbidden, neutron yield was observed in the two chambers. The spectra, as a function of lineal energy in the tissue equivalent chambers, clearly indicated a contribution from high energy neutrons. The yields were a significant fraction of the measurements between 10 and 25 keV.

We further performed Monte-Carlo calculations in order to estimate the

contribution of scattered neutrons to the detection of direct neutrons between 10 and 50 keV. The Monte-Carlo calculations considered the neutrons produced by the interaction of 1.95 MeV protons with the lithium target which scattered into the forward direction. The angular distribution of these neutrons was derived from Ref. 28. The neutrons were then allowed to elastically interact with the tungsten backing and the stainless steel surrounding the target, and the yield as a function of energy of scattered neutrons was compared with the scattering of neutrons produced by the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction. The calculations show that the contribution of scattered neutrons could be as large as 50, 30, and 15% for the measurements performed at 10, 15, and 25 keV respectively. Neutron energies varied between zero and the maximum neutron energy for the reaction (160 keV). The reason is that when the neutrons are elastically scattered by tungsten or stainless steel, they hardly change their initial energies, even if they are scattered to backward angles.

The Monte-Carlo calculations also showed that the contribution of scattering from the target vicinity into forward angles, in which neutrons with energies above 50 keV were measured, was small compared to the yield of the direct neutrons.

The experimental data presented for the energy region between 10 and 50 keV was corrected according to both the Monte-Carlo calculations and the calculations described in Section III. The data was also corrected for the flux removal by the material between the target and the tissue equivalent chamber. The data displayed in the following figures for these energies is the corrected data.

Figures 24 and 25 show the experimental data for the total number of particles above 10 keV/ μ for the 0.5 and 2 μ chambers, per incident dose equivalent of 1 mrem. The total number is normalized to 330, the average number of particles above 10 keV/ μ per mrem. Several observations can be made. First, the total number of counts per mrem (above 10 keV/ μ) for both the 0.5 and 2 μ chambers has maxima for both the lower energies around 70 keV and the higher energies above 3 MeV. It also has a minimum between 300 keV and 1 MeV. Second, the total number of particles above 10 keV/ μ in the neutron energy region between 50 and 100 keV is larger for the 2 μ chamber, reflecting the fact that at low energies the number of interactions in the gas of the 2 μ chamber is dominating. Third, the oscillatory behavior in the region of 10 keV to 14.5 MeV ranges within a factor of 3 for the 0.5 μ chamber. A factor of 3 also exists for

the 2μ chamber in the region of 50 keV to 14.5 MeV. It should be re-emphasized that the energies of the sources indicated in the figures are the dose equivalent-weighted average energies, and not the fluence-weighted average energies. For instance, the dose equivalent-weighted average energy for the D_2O -moderated ^{252}Cf spectrum is 2.2 MeV,^(32,33) whereas the fluence-weighted average energy for the same spectrum is 0.55 MeV.⁽³³⁾ For the other sources the fluence-weighted average energy is close to the dose equivalent-weighted energy.

Figures 26 and 27 show the spectroscopic information obtained from the experimental data, for the 0.5 and 2μ chambers respectively. This spectroscopic information is expressed as the ratio between the number of events in the (10-30) keV/ μ region and the total number of events above 10 keV/ μ . For both chambers this ratio peaks at low energies below 100 keV and at high energies above 3 MeV, while it has a minimum at energies near 600 keV. Naturally, the ratio between the number of particles in the region above 30 keV/ μ and the total number of particles peaks near 600 keV/ μ , as shown in Fig. 28 for the 0.5 μ chamber.

The spectroscopic information shown in Figures 26-28 was used to derive the dose equivalent, as explained in the theoretical results. The dose equivalent was represented as a linear combination of the total number of particles in only two regions: a) 10-30 keV/ μ and b) 30-120 keV/ μ . The dose equivalent (DE) in mrem, is expressed in the following way, for both the 0.5 and the 2μ chambers:

$$DE(mrem) = \frac{0.33N(10 - 30 \text{ keV}/\mu) + 2.27N(30 - 120 \text{ keV}/\mu)}{330} . \quad (27)$$

Figures 29 and 30 display equation (27) for the experimental data between 10 keV and 14.6 MeV. It can be observed that for the 0.5 μ chamber, equation (29) represents the dose equivalent within $\pm 20\%$ in the energy region of 25 keV to 14.6 MeV, and for the 2μ chamber within $\pm 20\%$ in the region of 60 keV to 14.6 MeV. It can be concluded that, for tissue equivalent chambers corresponding to tissue diameters in the range of 0.5 to 2μ , equation (27) represents the dose equivalent very well over a wide range of neutron energies.

V. SUMMARY AND CONCLUSIONS

The present study was divided into two parts. The first part was devoted to theoretical calculations which took into account only elastic scattering of neutrons with hydrogen atoms in the chamber wall and in the gas. Several realistic assumptions were made to simplify the calculations. We sought to identify a simple algorithm for calculating the dose equivalent from the measured data for a wide range of neutron energies. We placed emphasis on the energy region between 10 keV and 300 keV, since this region is of primary importance in power reactors and for most nuclear fuel processing. The algorithm was not to be microscopic, that is to derive the dose equivalent from the measurement of LET of the recoil particles in the tissue equivalent chambers. On the contrary, the calculations in the present study indicated that there is no correlation between the measured spectra as a function of the lineal energy and the LET of the recoil particles for neutron energies below 300 keV and for chambers of 1-2 μ equivalent diameter. The results are consistent with elaborate calculations carried out by Caswell.⁽¹⁰⁾ We conclude that previous studies,⁽⁴⁰⁾ which expressed the DE for chambers with a tissue-equivalent diameter of 2 μ as:

$$DE = k \sum_{i=1}^{i_2} N_i Y_i q_i, \quad (28)$$

are in error, especially in the region below 300 keV. In Eq. 28, k is a normalization factor, N_i is the number of pulses accumulated in channel i , corresponding to lineal energy Y_i . The quantity q_i , is the quality factor corresponding to a lineal energy Y_i .

At higher neutron energies, where Rossi's assumptions can be justified, the formalism to extract the distribution of particles in LET from the distribution of particles in lineal energy involves a differentiation method which is statistically limited for operations with portable instruments.

It is shown in the present study that, for neutron energies below 300 keV and especially for the 2 μ chamber, a) the number of protons generated in the gas is a significant fraction of the total number of protons depositing energy in

the gas, b) that the number of protons which are either stopped or lose a great fraction of their entrance energy in the gas becomes large, and c) the average track of the protons in the gas is not constant but rather increases with the neutron energy.

It should be mentioned that the calculations took into account only elastic scattering with hydrogen. These interactions are responsible for the main energy deposition in the gas. If the recoil of heavy charged particles was included, the conclusions expressed in (a)-(c) in the previous paragraph could have been much more pronounced. The assumptions made by Rossi may be valid for very low pressure proportional chambers of the order of 0.1μ in equivalent diameter. Such chambers are not practical because the energy deposition is very small, thus the number of pairs created in the gas is small. In such cases the energy resolution is poor and the interpretation of the data becomes difficult.

The quantity that can be naturally measured by low pressure tissue equivalent chambers is the kerma (K) which is expressed as follows:

$$K = k_1 \sum_{i=i_1}^{i_2} N_i E_i, \quad (29)$$

where k_1 is a normalization factor, E_i is the energy deposited corresponding to channel i , and N_i is the number of counts in channel i . However, even equation (29) is not completely accurate because the energy measured is not necessarily the deposited energy, but is the deposited energy folded with the resolution of the detector. Also, charge equilibrium does not necessarily exist in the gas volume for low neutron energies.

The calculations carried out in this study take into account the resolution of the detector. The response was expressed in a Gaussian form. The folding is important for low deposition energies; therefore, it has more significance for the measurements of the 0.5μ chamber than for the 2μ chamber.

Two sets of dE/dx values were used in the calculations (values derived from Andersen and Ziegler and those used by Auxier et al). The values of Auxier et al are lower than those of Andersen and Ziegler in the proton energy region

between 1 and 100 keV. Although these difference led to some differences in the calculated parameters, the conclusions regarding the measurements at low neutron energies were the same.

Although the calculations contain several simplifying assumptions and provide a qualitative picture, they describe quite well the experimental data. They facilitated the development of an algorithm for calculating the dose equivalent from the measured data. The algorithm considered the total number of recoiled particles above 10 keV/ μ divided into two regions, 10-30 keV/ μ and 30-120 keV/ μ . These regions serve as a spectroscopic tool for correcting the response of the total number of recoiled particles per mrem of incident neutrons, which was found to be oscillating as a function of the neutron energy and ambiguous for low and high neutron energies. The dose equivalent was expressed as a linear combination of the number of particles in the 10-20 keV/ μ and 30-120 keV/ μ regions. The expression for the dose equivalent reproduced the dose equivalent within $\pm 20\%$ in the region of 25 keV to 14.6 MeV for the 0.5 μ chamber. This formalism can easily be utilized in a portable instrument without using an ADC.

To test the theoretical calculations, an experimental investigation of the performance of chambers with tissue equivalent diameters of 0.5 and 2 μ was conducted by irradiating the chambers with monoenergetic and polyenergetic neutron sources. Monoenergetic neutrons in the range of 10 keV to 1 MeV were produced from the reaction ${}^7\text{Li}(p,n){}^7\text{Be}$, at 2.5 MeV from $\text{D}(d,n){}^3\text{He}$ and at 14.6 MeV with the $\text{T}(d,n){}^4\text{He}$ reaction. Polyenergetic sources included bare ${}^{252}\text{Cf}$, D_2O -moderated ${}^{252}\text{Cf}$, ${}^{238}\text{Pu-F}$, ${}^{238}\text{Pu-B}$, and ${}^{238}\text{Pu-Be}$. In most cases absolute fluences and dose equivalents were determined using a long counter of the East and Walton⁽²⁴⁾ type. The experiments at energies below 300 keV proved that the correlation between lineal energy and LET of the recoiling particles is not straightforward. The spectra, as a function of lineal energy, showed a large dependency on the equivalent tissue diameter of the chamber. At energies higher than 1 MeV, the two chambers showed similar spectra.

The efficiency of the chambers used in this study (5.7 cm physical diameter) is quite low. The average number of particles above 10 keV/ μ is about 300 per mrem, which implies 0.1 counts per sec per mrem/h. In a 3 sec integration period, the minimum dose equivalent rate to be detected with reasonable accuracy ($\pm 25\%$) is about 100 mrem/h. For most applications, a range from 1 to 100 mrem/h is required. Thus, low pressure spherical tissue

equivalent chambers are not useful as dose equivalent rate meters, unless the integration period or the chamber size is significantly increased. However, they are very useful for dose equivalent measurements with a long integration period.

In order to obtain a sensitivity comparable to a SNOOPY rem meter,⁽⁴¹⁾ i. e. 8000 counts per mrem, a tissue equivalent chamber with a diameter of about 28 cm is needed. This in principle is achievable but probably would be expensive. However, such an instrument would still be much lighter than a SNOOPY and less cumbersome. The instrument would measure the dose equivalent, using equation (27) to within $\pm 20\%$ of the expected value in the region of 25 keV to 14.6 MeV. This is a much better response than that of a SNOOPY,⁽⁴¹⁾ which over-responds by at least a factor of 2 at 25 keV, and under-responds by a factor of 3 at 14.6 MeV.

Another approach is now used by several laboratories.^(42,43) In this approach high pressure proportional chambers, filled with a hydrogen-rich mixture, are used. The recoil protons are usually stopped in the gas, and the energy deposited spectrum gives information about the incident neutron spectrum. At low neutron energies, the sensitivity of these detectors is much greater than for low pressure chambers. At high energies, such as 14.6 MeV, very high pressures are needed in order to stop most of the recoil protons.

A small, light weight, portable rem-meter, based on Eq. (27), and utilizing a 0.5μ tissue equivalent chamber, has been thoroughly field-tested.⁽⁴⁴⁾ The instrument is microprocessor-based with self-test circuitry for stability and calibration. The instrument displays the raw spectrum as a function of lineal energy, the dose equivalent, and the dose equivalent rate.

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Fig. 1. Coordinate system for neutron interactions with the wall of the chamber.

Fig. 2. Schematic diagram of the experimental setup for the ${}^7\text{Li}(p,n){}^7\text{Be}$ neutron irradiation.

Fig. 3. Schematic diagram of the experimental setup for the $\text{D}(d,n){}^3\text{He}$ neutron irradiations.

Fig. 4. Schematic diagram of the experimental setup for the $T(d,n)^4\text{He}$ neutron irradiations.

Fig. 5. Calculated energy deposition spectra of recoil protons as a function of the lineal energy for the 0.5 μ tissue equivalent chamber. Incident neutron energies ranged from 8 to 69 keV as noted.

Fig. 6. Calculated energy deposition spectra of recoil protons as a function of the lineal energy for the 2 μ tissue equivalent chamber. Incident neutron energies ranged from 8 to 69 keV as noted.

Fig. 7. Calculated energy deposition spectra of recoil protons as a function of the lineal energy for 0.5 and 2 μ chambers, and for 93 keV neutron energy (arbitrary units).

Fig. 8. Calculated ratio (R_2) between the number of protons below 10 keV/ μ to the total number of protons as a function of the neutron energy for 0.5 and 2 μ tissue equivalent chambers.

Fig. 9. Calculated energy deposition spectra of recoil protons as a function of the lineal energy for 1 MeV incident neutrons and for 0.5 and 2 μ chambers.

Fig. 10. Calculated ratio (R_1) between the number of protons generated in the wall and stopped in the gas and the total number of protons generated in the wall that reach the gas, for the 0.5 and the 2 μ chambers.

Fig. 11. Calculated ratio (R) between the number of protons generated in the gas and the total number of protons generated in both the wall and the gas, for the 0.5μ and 2μ chambers.

Fig. 12. Calculated ratio between the average track length (D_{ave}) in the gas for recoil protons generated in both the wall and the gas and the maximum average track length (D_{eff}) at high neutron energies. Calculations are for the 0.5μ and 2μ chambers.

Fig. 13. Calculated detector response for the 0.5 μ chamber, expressed as the number of recoil protons above 10 keV/ μ and normalized to the average value of 330 per mrem.

Fig. 14. Calculated detector response above an energy deposition of 10 keV/ μ for the 2 μ chamber, expressed as in Fig. 13.

Fig. 15. Calculated ratio (Z) between the number of recoil protons in the region between 10-30 keV/ μ and the total number of recoil protons in the region of 10-120 keV/ μ , for the 0.5 μ chamber. Solid and dashed lines are calculations using stopping power values from Anderson and Ziegler⁽¹⁸⁾ and Auxier et al.⁽¹⁹⁾ respectively.

Fig. 16. Calculated ratio (Z) between the number of recoil protons in the region of 10-30 keV/ μ to the total number of recoil protons in the region of 10-120 keV/ μ , for the 2 μ chamber. Solid and dashed lines are calculations using stopping power values from Anderson and Ziegler⁽¹⁸⁾ and Auxier et al.⁽¹⁹⁾ respectively.

Fig. 17. Calculated ratio (Z_1) between the number of recoil protons in the region >30 - 120 keV/ μ to the total number of recoil protons in the region of 10 - 120 keV/ μ , for the 0.5μ chamber.

Fig. 18. Experimental energy deposition spectra as a function of lineal energy for 50 keV incident neutrons and for the 0.5 and the 2μ chambers. Neutrons were generated in the ${}^7\text{Li}(p,n){}^7\text{Be}$ reaction. The chambers were positioned symmetrically about the beam line and thus received the same number of incident neutrons.

Fig. 19. Experimental energy deposition spectra as in Fig. 18 for 100 keV incident neutrons.

Fig. 20. Experimental energy deposition spectra as in Fig. 18 for 300 keV incident neutrons.

Fig. 21. Experimental energy deposition spectra as in Fig. 18 for 900 keV incident neutrons.

Fig. 22. Experimental energy deposition spectra in the 2μ chamber for incident neutron energy of 15 keV.

Fig. 23. Experimental detector response for the 0.5 μ chamber, expressed as the total number of particles above 10 keV/ μ and normalized to the average value of 330 per mem. Data are from experiments with both monoenergetic (.) and polyenergetic (Δ) neutron sources.

Fig. 24. Experimental detector response for the 2 μ chamber, expressed as in Fig. 23.

Fig. 25. Experimental ratio (Z) between the number of recoil particles in the region of (10-30) keV/ μ and the total number of recoil particles in the region of (10-120) keV/ μ , for the 0.5 μ chamber. Symbols are as in Fig. 23.

Fig. 26. Experimental ratio (Z) between the number of recoil particles in the region of (10-30) keV/ μ and the total number of recoil particles in the region of (10-120) keV/ μ for the 2 μ chamber. Symbols are as in Fig. 23.

Fig. 27. Experimental ratio (Z_1) between the number of recoil protons in the region (30-120) keV/ μ to the total number of recoil particles in the region (10-120) keV/ μ for the 0.5 μ chamber. Symbols are as in Fig. 23.

Fig. 28. The dose equivalent response (in mrem, given by Eq. 26) as a function of the incident neutron energy for the 0.5 μ chamber. The quantities $N(10-30 \text{ keV}/\mu)$ and $N(30-120 \text{ keV}/\mu)$ are the experimental number of particles in the (10-30) keV/ μ and (>30-120) keV/ μ regions, respectively. Symbols are as in Fig. 23.

Fig. 29. The dose equivalent response as in Fig. 29 for the 2 μ chamber. Symbols are as in Fig. 23.