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Characterization of the neutron environment around Varian medical electron accelerators

Mashal M. Elsalim
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DOI: <https://doi.org/10.31979/etd.e2b6-hyfp>
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**Characterization of the neutron environment around Varian
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Elsalim, Mashal M., M.S.

San Jose State University, 1994

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CHARACTERIZATION OF THE NEUTRON ENVIRONMENT
AROUND VARIAN MEDICAL ELECTRON ACCELERATORS

A Thesis

Presented to
The Faculty of the Department of Nuclear Science
San Jose State University

In partial Fulfillment
of the Requirements for the degree
Master of Science

By
Mashal M. Elsalim

August, 1994

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ABSTRACT

CHARACTERIZATION OF THE NEUTRON ENVIRONMENT AROUND VARIAN MEDICAL ELECTRON ACCELERATORS

by Mashal M. Elsalim

This work presents results of a study to measure the neutron spectra around Varian medical linear accelerators of differing X-ray beam energies (10 MV, 15 MV, 18 MV and 20 MV) using three different neutron detection methods. The three neutron detection systems used include a Bonner sphere spectrometer with ^6LiF and ^7LiF TLD pair as the thermal neutron detector (BSS), a bubble detector spectrometer (BDS), and indium activation foils used with both a fluence moderator and an Anderson-Braun remmeter. These three detection systems were calibrated using a ^{252}Cf neutron source at Stanford Linear Accelerator Center. The BUNKI code was used to unfold spectra for the BSS and the BDS data. A spectral stripping method of unfolding was applied to the BDS data as well. The data from the fluence moderator and the Andersson-Braun remmeter were analyzed to give neutron fluence and other dosimetric quantities for comparison with the other methods, but no spectral information was obtained.

Results of the spectral measurements from the BSS indicated spectral dependence based on the measurement location and accelerator energy. The BDS-BUNKI spectra gave similar results.

ACKNOWLEDGMENTS

This writer would like to express appreciation and thanks to some of the people who helped and without whom this study would not have been possible. Dr. Peter Englert encouraged me to come to the health physics program and directed my studies. Dr. Jeff Kleck of Varian Associates, Inc. provided most of what was needed to complete the project in addition to his helpful insights. Dr. James Liu and Dr. Vashek Vylet of the Radiation Physics Group at SLAC helped in the calibration setup and the unfolding codes and interpreting some of the data for the Bubbie detectors and the Bonner spheres. Dr. David Findley, Dr. Peter Fessenden, and Mr. Mark Wanlass of Stanford University Medical Center provided resources, time, and assistance. The Dosimetry laboratory staff at SLAC provided the TLD calibration equipment and readers. Mr. Norman L. McElroy offered valuable input and helpful suggestions. The support staff at Varian Associates provided computer and drafting assistance.

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CHAPTER I

INTRODUCTION

Neutron dosimetry for radiation protection purposes around medical electron linear accelerators (LINACs) is a very complex and challenging undertaking, due principally to the complex nature of the instrumentation and methods available for the task. Field surveys with active neutron monitors can provide information which can be used to confirm the integrity of existing shielding. However, in order to adequately design accelerator room shielding there is a need to understand the character and the transport of accelerator produced neutrons, as they pose one of the dominant radiation protection problems at higher energies available on medical LINACs. Fundamental to this understanding is access to the neutron spectra produced around medical LINACs. A knowledge of the neutron spectral distribution facilitates the calculation of dose equivalent, which is the basic unit for any radiation protection program. The assessment of dose equivalent is facilitated by the use of the appropriate fluence-to-dose equivalent conversion factors convoluted with the neutron field spectra.

The use of high energy accelerators as a source of x-rays and electrons for radiotherapy has increasingly become an important feature of health centers around the world. With accelerator energies greater than 10 MV, neutrons become an important component of an already complicated radiation field consisting of leakage photons from the head, scattered photons from treatment room walls and from the patient and other objects in the treatment room, and from photons produced in places other than the target [1].

For the present day medical LINACs, neutron production is caused by the "giant resonance" [2]. The primary mode of neutron production is via (γ, n) reactions, with lesser amounts produced by (γ, pn) and $(\gamma, 2n)$ reactions, provided the photon energy is sufficient. The photoneutron cross sections of materials usually used in the design of electron LINACs beam transport systems are characterized by a threshold energy, a gradual increase to an evident peak at about 12-18 MeV, and then a decrease at higher photon energies [3]. The absolute yield of photoneutron production is dependent on the magnitude of this "giant resonance" cross section [4]. Direct neutron production by electrons is a few orders of magnitude smaller than by photonuclear reactions and can be ignored [2].

There are two processes that contribute to the neutron spectra in the giant resonance. The larger process component, called the evaporation spectrum, can be adequately described by a Maxwellian distribution:

$$\frac{dN}{dE_n} = \frac{E_n}{T^2} \exp\left(-\frac{E_n}{T}\right) \quad (1)$$

where T is the nuclear temperature in MeV for the particular residual nuclide after the neutron has been emitted, and is a function of the excitation energy. E_n is the neutron energy in MeV, and N is the number of neutrons. Evaporation neutrons are emitted almost isotropically from the point of origin.

The direct emission is responsible for the production of the second group of neutrons from the giant resonance. Direct emission neutrons are characterized by having higher energy than the evaporation neutrons, and they account for about 14 percent of the total photoneutron production. The angular distribution

of the direct neutrons are usually anisotropic with respect to the photon beam direction [5].

Medical LINACs have massive shielding around the target referred to as the primary collimator, which serves a dual function as a shield against photons, and as a beam collimator. Medical LINACs treatment head shielding is comprised of high atomic number materials, such as steel, lead, and tungsten. The treatment head also contains materials such as iron and copper used in the design of the bending magnets, and steel and aluminum to provide structural support.

High atomic number materials provide excellent photon shielding. These materials play a role in photoneutron production but are relatively ineffective in attenuating neutrons. The most significant energy loss mechanisms of neutrons in heavy materials are inelastic scattering and (n,2n) reactions. The non-elastic cross section, σ_{non} , is the sum of inelastic and (n,2n) cross sections. Even though σ_{non} is almost the same for tungsten and for lead [2], tungsten is considerably more effective in reducing neutron energy than lead. This is because tungsten has an atomic density of 6.25×10^{22} atoms cm^{-3} , compared to the 3.28×10^{22} atoms cm^{-3} for lead. Additionally inelastic scattering in tungsten extends to much lower energies while Lead is virtually transparent to neutrons at low energies (i.e. less than 0.5 MeV) [2].

The literature presents the results of several studies performed to characterize neutron fields in the vicinity of medical linear accelerators [1,2,4,5,6,7,8,9]. However, many of these studies were done for only one accelerator energy, or used a neutron detection method that was not appropriate given the nature of the radiation field produced by accelerators, or for a small

sampling of measurement locations. In addition there have been very few studies of neutron spectral measurements in close proximity to the accelerator head.

The principal motive for this study is to make as complete an assessment as possible of the neutron environment around Varian Clinac 1800, 2100C, 2100C/D, and 2300C/D classes of medical LINACs, to include neutron spectra, dose equivalent, and neutron fluence measurements. In this study we will characterize the neutron spectra around medical LINACs of differing energies using three independent methods. The three methods employed were the Bubble Detector Spectrometer (BDS), the Bonner Sphere Spectrometer (BSS), and the moderated indium foil activation (fluence moderator and an Anderson-Braun type remmeter combination).

Four LINACs of neutron producing energies (10, 15, 18, and 20 MV) manufactured by Varian at the time of the study were selected. The choice of the three systems allows for inter-method comparison. The passive neutron detection technique is chosen due to monitoring limitations associated with the intermittent nature of the radiation field produced by the accelerator's pulsed operation. The pulsed character of the radiation renders most active detection methods useless. Four different measurement locations were selected to more fully represent the neutron field around the accelerator head. These locations are illustrated in Figure 1.1. Positions A and B are in the patient plane, 40 cm and 100 cm from isocenter, respectively, and correspond to measurement positions specified by the International Electrotechnical Commission [10]. Positions in the patient plane were chosen for their clinical significance. Position C is in the target plane at a distance of 100 cm from the target, and position D is above the

Figure 1.1. Measurement positions around the accelerator. Positions A through D are common to each of the three detection methods. This coordinate system is based on the fixed coordinate system proposed in the International Electrotechnical Commission Draft standard [10]. Courtesy of Varian Associates, Inc.

treatment head also 100 cm from the target. Positions C and D were selected to help address room shielding issues. Measurements were performed with the gantry in the upright position, and the collimator jaws were closed. Machines used in this study had completed all phases of manufacturing, testing, and calibration. No phantoms were used in conjunction with this study.

A plan view of a typical accelerator facility is shown in Figure 1.2. Table 1.1 gives the dimensions of the various cells used in this study. These cells have a single shield door constructed of 2.54 cm of borated-polyethylene, plus 20 cm of polyethylene, plus 15 cm of lead, with a 1.27 cm thick steel plate on both sides of the door, and no maze. All measurements were made in the test cells at Varian (911 Hansen way, Palo Alto, Ca.), with the exception of the 15 MV machine measurements (BSS and BDS systems) which were made at the delivery site (Stanford Medical Center). This room had an irregular shape with an inside surface area of $1.6 \times 10^6 \text{ cm}^2$. It should be noted that this room also had 2.54 cm of 5% borated-polyethylene lining the interior.

Table 1.1

Room dimensions in meters of the cells used in this study.

Machine	Width (m)	Length (m)	Height (m)
10	5.79	7.01	4.57
15 ¹	6.71	7.14	4.75
18	6.70	8.38	4.75
20	7.01	7.42	4.75

¹ The moderated indium foil activation measurements were performed in the test cells at Varian, 911 Hansen way, Palo Alto, Ca. The BSS and BDS measurements were made at Stanford Medical Center, Stanford, Ca.

Figure 1.2. Plan of a typical accelerator facility. Courtesy of Varian Associates, Inc.

Chapter II of this document introduces the Bubble Detector Spectrometer (BDS). A description of the experimental setup and the data acquisition procedure are discussed. Results utilizing two different analytical methods of the neutron fluence, dose equivalent, and spectral measurements are presented. The first method of analysis is the spectral stripping technique and will be referred to as BDS spectral stripping technique. The second analytical method is using the BUNKI unfolding code, a computer program written in FORTRAN IV devised by Lowry and Johnson of the Naval Research Laboratory, and will be referred to as the BDS-BUNKI method in this document.

In chapter III, the Bonner Sphere Spectrometer will be discussed. Data analysis using the BUNKI code will be explained, and dosimetric quantities as calculated by the code are presented. A sample of the resulting spectral measurements will also be shown. This method will be referred to as the BSS method.

Chapter IV presents the moderated indium foil activation detection method. Fluence calculations based on the method of the American Association of Physicists in Medicine (AAPM) report number 19 will be presented. The results of the dose equivalent measurements and average energy calculations based on data from NCRP report 79 will be provided, and compared with the results obtained using half-energy-layer (HEL) calculations.

Chapter V is a comprehensive summary of all of the results from each of the methods. Comparisons between the three methods for the different accelerator energies and measurement positions will be discussed in this chapter.

An introduction to the neutron detection methods used in this study and the results of their calibration is addressed in a separate dissertation by the co-

researcher of this project [11]. Although this author was involved in all aspects of the research, it was found necessary to divide the study at the logical separation point to satisfy the academic needs of both researchers. Hence, the focus of this work will be on the accelerator portion of the study. For background, the reader is encouraged to consult the radioisotopic portion of this study [11].

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Chapter II

BUBBLE DETECTOR SPECTROMETER

2.1 INTRODUCTION

The Bubble Detector Spectrometer (BDS), developed at Chalk River Laboratory, Canada, and manufactured by Bubble Technology Industries, Inc. (BTI), was used in this experiment. The BDS operates on the same principle as the bubble chamber discovered by Glaser in 1952 [1].

The BTI detectors consist of tiny superheated liquid droplets that are dispersed throughout an elastic polymer. This polymer is housed in a small sealed and capped plastic test tube. A low boiling point liquid floating above the polymer keeps it insensitive to radiation by exerting pressure on the polymer. By removing the cap for the first time and discharging the liquid, the detector becomes sensitized and ready to detect neutrons [2]. The theory of neutron detection with superheated liquids is covered in the literature [3,4,5]. Additionally, the first part of this study [6] delves into more detail on the subject of superheated liquids in neutron detection. Hence it will not be discussed further in this work. The experimental procedure and the results of using the BDS system as a neutron spectrometer will be presented in this chapter.

2.2 EXPERIMENTAL SETUP

The Bubble Detector Spectrometer (BDS) used in this study consisted of six energy thresholds at 10 keV, 100 keV, 600 keV, 1 MeV, 2.5 MeV and 10 MeV. There are six detectors in each energy threshold, constituting a total of 36 detectors in the BDS set. In order to get good counting statistics, we used all six

detectors of each energy group, one group at a time, at each measurement position. For position A, for example, all six detectors of energy group 10 keV (called BDS-10) were irradiated together, then they were replaced by all six detectors of the BDS-100, BDS-600, BDS-1000, BDS-2500, and BDS-10000, respectively. The same process was repeated three times for each location, for a total of 18 measurements at each position in each energy group.

Four locations around the accelerator were chosen to perform spectral measurements. A diagram illustrating these positions relative to the accelerator head was presented in Figure 1.1. These locations were deemed representative of the neutron environment around a medical LINAC.

The detectors were mounted on a Styrofoam holder with holes to hold them in place with reproducible geometry, and a hole in the middle to mount this holder on a pole for vertical positioning. The Styrofoam holder allowed us to position the detectors exactly the same way each time they are irradiated. The same mounting apparatus used in these measurements was also used in the calibration setup [6].

The spectrometer set was calibrated by the manufacturer, BTI, to determine its sensitivity to neutrons at a temperature of 20°C. The energy response of the detectors is temperature-dependent, and this dependence is not well characterized [7]. Hence, the temperature of the detectors must be kept at 20°C before and during irradiation to minimize the effect. The temperature was maintained by means of placing the detectors in a water bath at 20°C prior to irradiation until they reached equilibrium. In addition, the room temperature of the cell in which the irradiation occurred was maintained at 20°C. The duration of the irradiation for each detector set at each position was pre-determined based

on several factors: the average sensitivity of the six detectors provided by BTI, the dose rate delivery of the electron accelerator, the location of irradiation, and the number of bubbles desired in each individual detector. After irradiation, the detectors were set aside (not in the water bath) for few minutes (15-30 minutes) to allow visual counting of the bubbles. These bubbles are immobile in the firm gel, and are easily recompressed after counting by use of a pressure vessel designed for this purpose. Bubbles will grow larger and become very hard to decompress if left for an extended time period (i.e. > 24 hours).

2.3 DATA ANALYSIS

After irradiation, each detector was placed on a lighted table and bubbles were counted by eye four times for accuracy, twice by the author, and twice by the co-researcher of this study. The number of bubbles formed is a measure of the neutron fluence. The four counts per detector were averaged, and the averaged values from all six detectors of the same group were then averaged to obtain the number of bubbles in each energy group for use in the data analysis. The goal of this study is to provide spectral profiles of the neutron fields around medical electron accelerators, but other important quantities can also be determined, such as the neutron fluence in each energy group, the average neutron energy, and the neutron dose equivalent. Such information is invaluable in the area of patient dosimetry and facility shielding.

2.3.1 Spectral Stripping Calculations

As stated previously, a primary goal of this study was to determine the neutron spectrum at the specified positions. In the radioisotopic publication

portion of this project [6], a method for calculating the neutron fluence in each energy bin called the spectral stripping method, devised by Ing to manually calculate the spectra [5], was illustrated. Figures 2.3 through 2.6 represent the spectra for positions A through D for the 18 MV accelerator using this BDS-stripping method. The calculated spectra for one accelerator (18 MV) is presented here for illustration; the rest of the spectral data for all four accelerators and all positions exhibited similar features and are included as digital data in Appendix C of this document.

2.3.2 Neutron Fluence Calculations

The number of bubbles measured in each detector group will be an indicator of the neutron fluence in the corresponding neutron energy bin. This neutron fluence is then used in the spectral stripping method to obtain the measured neutron spectra. The method for obtaining neutron fluence from the number of bubbles is straightforward, and is illustrated in Appendix D of the radioisotopic portion of this study [6].

2.3.3 Fluence-to-Dose-Equivalent Conversion Factors

For this study, the fluence-to-dose-equivalent conversion factors (h_ϕ) from ICRP Publication 21 [8] were used to convert measured fluence results to dose equivalent values.

The BDS system uses six energy intervals from 10-100 keV, 100-600 keV, 600-1000 keV, 1000-2500 keV, 2500-10000 keV, and from 10000-20000 keV respectively. In order to perform any calculation regarding dose equivalent or average energy from fluence spectrum, certain assumptions have to be made

Figure 2.3. The neutron spectra plotted as the fluence versus neutron energy for the 18 MV accelerator at position A. This plot was obtained using the stripping method for the BDS detectors. Digital data are presented in tables in appendix C.

Varian 18 MV Position (B) BDS, Stripping method

Figure 2.4. The neutron spectra plotted as the fluence versus neutron energy for the 18 MV accelerator at position B. This plot was obtained using the stripping method for the BDS detectors. Digital data are presented in tables in appendix C.

Varian 18 MV Position (C) BDS, Stripping method

Figure 2.5. The neutron spectra plotted as the fluence versus neutron energy for the 18 MV accelerator at position C. This plot was obtained using the stripping method for the BDS detectors. Digital data are presented in tables in appendix C.

Figure 2.6. The neutron spectra plotted as the fluence versus neutron energy for the 18 MV accelerator at position D. This plot was obtained using the stripping method for the BDS detectors. Digital data are presented in tables in appendix C.

about the shape of the neutron fluence within these energy bins. Two assumptions were used in this study: a constant fluence distribution, and one that varies as $1/E$ within each energy group. The h_ϕ values are then determined using the data from ICRP Publication 21, and the assumptions concerning the neutron fluence distribution within each energy interval. The h_ϕ calculations are illustrated in Appendix C of the radioisotopic part of this study [6]. Table 2.1 presents a summary of these calculations.

Table 2.2 summarizes the neutron fluence measurement results at the four positions for the four LINACs utilized in this study. Tables 2.3 and 2.4 show the measured dose equivalent results based on the $1/E$ fluence assumption, or the constant fluence assumption respectively. It should be noted that all the fluence and dose equivalent results in this thesis have been normalized to 1 Gy of photon dose delivered at isocenter.

Table 2.1

The Fluence-to-Dose-Equivalent Conversion Factors (h_ϕ) calculated with the constant and $1/E$ assumption regarding the neutron fluence. Values are in units of 10^{-10} Sv cm².

BDS Energy interval	Constant fluence	1/E
10 - 100 keV	0.355	0.270
100 - 600 keV	1.479	1.236
600 - 1000 keV	2.830	2.784
1000 - 2500 keV	3.803	3.738
2500 - 10000 keV	4.060	4.060
10000 - 20000 keV	4.060	4.060

Table 2.2

The total neutron fluence [$\text{cm}^{-2} \text{Gy}^{-1}$] measured by the BDS using the spectral stripping method.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	1.39E+06	9.72E+05	1.16E+06	1.21E+06
15 MV	1.32E+07	9.04E+06	1.07E+07	1.57E+07
18 MV	3.90E+07	2.94E+07	3.10E+07	4.57E+07
20 MV	3.81E+07	2.86E+07	3.93E+07	4.53E+07

Table 2.3

The dose equivalent [Sv Gy^{-1}] measured by the BDS, using the spectral stripping method and the 1/E fluence assumption.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	6.58E-05	4.71E-05	5.94E-05	6.10E-05
15 MV	7.71E-04	5.94E-04	7.34E-04	9.47E-04
18 MV	2.20E-03	1.66E-03	2.21E-03	2.58E-03
20 MV	2.34E-03	1.14E-03	1.51E-03	3.04E-03

Table 2.4

The dose equivalent [Sv Gy⁻¹] measured by the BDS, using the spectral stripping method and the constant fluence assumption.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	7.77E-05	5.50E-05	6.90E-05	7.10E-05
15 MV	8.87E-04	6.66E-04	8.19E-04	1.08E-03
18 MV	2.53E-03	1.91E-03	2.55E-03	2.96E-03
20 MV	2.65E-03	1.36E-03	1.84E-03	3.41E-03

2.3.4 Average Energy

The previous assumptions regarding neutron fluence within the various energy intervals are used in the calculation of average energy using the stripping method. If a constant fluence is assumed, the average energy can be calculated using the following equation:

$$\bar{E} = \frac{\sum_{i=1}^6 \frac{\Phi_i}{(E_{i+1} - E_i)} * \int_{E_i}^{E_{i+1}} E dE}{\sum_{i=1}^6 \Phi_i} \quad (1)$$

where: the summation is over all six energy intervals, E_i and E_{i+1} are the lower and upper limits of each energy interval respectively, and Φ_i is the neutron fluence measured in that interval, and is treated as a constant. If the fluence is assumed to vary as $1/E$, the above equation becomes:

$$\frac{\sum_{i=1}^6 \frac{\Phi_i \cdot (E_{i+1} - E_i)}{\ln\left(\frac{E_{i+1}}{E_i}\right)}}{\sum_{i=1}^6 \Phi_i} \quad (2)$$

Tables 2.5 and 2.6, below, list the calculated average neutron energies for all four accelerators by position using the 1/E and the constant fluence shape assumptions, respectively.

Table 2.5

Average energy [MeV] measured by the BDS using the spectral stripping method and the 1/E fluence assumption.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	0.10	0.11	0.11	0.11
15 MV	0.15	0.19	0.18	0.16
18 MV	0.15	0.16	0.14	0.14
20 MV	0.18	0.21	0.10	0.19

Table 2.6

Average energy [MeV] measured by the BDS using the spectral stripping method and the constant fluence assumption.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	0.12	0.13	0.13	0.13
15 MV	0.18	0.21	0.20	0.18
18 MV	0.17	0.18	0.16	0.16
20 MV	0.20	0.24	0.12	0.21

2.3.5 Spectral Unfolding using BUNKI

The BUNKI code [11] was used as another method to calculate the spectra obtained with the BDS system. The standardized responses from the six energy intervals, calculated in accordance with the method illustrated in Appendix D of the radioisotopic portion of this study [6], were used as input for BUNKI. Based on this input, BUNKI calculates the total neutron fluence (cm^{-2}), average energy (MeV), dose equivalent (rem), a quality factor, and a fluence per unit lethargy for 31 energy bins. Tables 2.7 through 2.10 below are summaries of BUNKI's outputs of the various dosimetric quantities. All output values were converted to SI units. The fluence per unit lethargy was plotted to obtain the spectra represented by the graphs in Figures 2.7 through 2.10. These graphs are for the 18 MV accelerator, with the remaining data from the other four accelerators presented in Appendix A.

Table 2.7

Total neutron fluence [$\text{cm}^{-2} \text{Gy}^{-1}$] measured by the BDS-BUNKI method.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	8.07E+05	5.03E+05	7.14E+05	7.30E+05
15 MV	6.56E+06	4.67E+06	6.07E+06	8.46E+06
18 MV	2.05E+07	1.51E+07	2.11E+07	2.28E+07
20 MV	1.90E+07	1.17E+07	2.11E+07	1.75E+07

Table 2.8

Dose equivalent [Sv Gy^{-1}] measured by the BDS-BUNKI method.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	5.10E-05	3.67E-05	4.79E-05	4.84E-05
15 MV	6.17E-04	4.77E-04	5.97E-04	7.63E-04
18 MV	1.74E-03	1.32E-03	1.76E-03	2.06E-03
20 MV	1.86E-03	1.55E-03	2.04E-03	2.34E-03

Table 2.9

Average energy [MeV] measured by the BDS-BUNKI method.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	0.14	0.17	0.16	0.16
15 MV	0.26	0.29	0.26	0.24
18 MV	0.23	0.25	0.22	0.24
20 MV	0.29	0.41	0.27	0.40

Table 2.10

Quality factors measured by the BDS-BUNKI method.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	6.8	7.3	7.0	7.0
15 MV	8.0	8.2	8.2	7.9
18 MV	7.7	7.7	7.7	7.9
20 MV	8.1	8.9	8.1	9.0

Figure 2.7. The fluence per unit lethargy versus the log of the neutron energy for the 18 MV accelerator at position A. This plot was obtained using the BUNKI code unfolding method for the BDS detectors. Digital data are presented in tables in appendix A.

Figure 2.8. The fluence per unit lethargy versus the log of the neutron energy for the 18 MV accelerator at position B. This plot was obtained using the BUNKI code unfolding method for the BDS detectors. Digital data are presented in tables in appendix A.

Figure 2.9. The fluence per unit lethargy versus the log of the neutron energy for the 18 MV accelerator at position C. This plot was obtained using the BUNKI code unfolding method for the BDS detectors. Digital data are presented in tables in appendix A.

Figure 2.10. The fluence per unit lethargy versus the log of the neutron energy for the 18 MV accelerator at position D. This plot was obtained using the BUNKI code unfolding method for the BDS detectors. Digital data are presented in tables in appendix A.

2.5 DISCUSSION

An important factor that the BUNKI code depends on is a thorough knowledge of the detector response matrices [11]. The detector response matrix added to the BUNKI code by the SLAC group to allow unfolding of the BDS data was provided by the manufacturer of the BDS system, BTI [7]. No calculations were made independently to verify these responses. Hence, the spectra and the dosimetric quantities calculated by BDS-BUNKI method are dependent on the quality of this response matrix.

The neutron spectra obtained by the BDS-BUNKI method showed two principal peaks instead of one. These two peaks are not seen in the spectra using the stripping method. The spectra obtained with the stripping method were plotted as the neutron fluence per energy bin versus neutron energy. This method of plotting spectra allows the comparison of the fluence in each bin based on the height of the fluence in that bin. The BUNKI spectra were plotted as the neutron fluence per unit lethargy versus the log of the neutron energy, where the comparison here is based on the area of each energy bin and not the magnitude of the height of the fluence. The stripping method is a crude estimate of the neutron spectrum, since it uses a small number of energy bins (only six). Another shortcoming of the method is the large statistical fluctuation in the number of bubbles obtained in some of the bins. The last energy bin has the largest statistical fluctuations in the number of bubbles detected, a standard deviation of 100 percent in some instances. The spectral stripping technique uses the last energy bin first in the unfolding of the neutron spectra. Hence, a large error due to the statistical fluctuations in this bin are propagated to other bins.

These energy bins are also very wide and the assumptions regarding the shape of the fluence as a constant or $1/E$ may not be adequate.

The neutron fluence from the BDS-BUNKI in Table 2.7 shows a dependence on the accelerator energy. The fluence increases as the energy increase and the magnitude reflects the distance of each position from the x-ray target. A comparison of total fluence between the BDS stripping method output and the BDS-BUNKI output indicates a general agreement within a factor of 2 to 3.

The BDS-BUNKI output of average energy exhibited similar energy- and position-dependent trends as the stripping method output. However, the BDS-BUNKI output values were almost double the values of the stripping method. This may be attributed to the difference in the way the bins that are used in BUNKI are structured (31 rebined energy bins from 6 detector inputs) versus that of the stripping method (6 bins); hence, the fluctuations within each energy bin are less severe for the BUNKI method. In addition, because the BUNKI-BDS energy bins are narrower, the method becomes sensitive to the variations of the detectors' energy response.

Dose equivalent results presented in Tables 2.3 and 2.4 show an accelerator energy dependence that is increasing with increasing accelerator energy. Dose equivalent values using the constant fluence assumption are higher than that of the $1/E$ fluence assumption by as much as 25 percent. This difference comes directly from the integrals in the calculation of the $h\phi$. The BUNKI output of dose equivalent values are within a factor of 2 less, but comparable to, the $1/E$ fluence assumption values from the spectral stripping method. Hence, this reflects the fact that the true spectrum within each energy

bin is more likely to be $1/E$ than constant, as it should. In general the calculated dose equivalent values from the BDS-BUNKI and the stripping method, demonstrate better agreement than the calculated fluences.

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Chapter III

BONNER SPHERE SPECTROMETER

3.1 INTRODUCTION

A neutron spectrometer consisting of thermal neutron detectors mounted inside polyethylene spheres of various diameters, to give the detectors an individual response versus energy function, was first investigated in 1960 by Bramblett *et al.*[1]. Such a spectrometer is widely known as a Bonner Sphere Spectrometer (BSS), after T. W. Bonner.

Several types of thermal neutron detectors can be used with the BSS system [1][2][3]. The ^6LiF thermoluminescent dosimeter (TLD) is the thermal neutron detector of choice in this study.

In recent years, the thermoluminescent dosimeter (TLD) has been used frequently. The operation of the TLD exploits the light emission properties of certain crystals, such as LiF, when heated after exposure to radiation. For a thorough discussion of the properties and applications of various TLD materials, the reader is advised to consult the literature [3][4][5].

Two pairs of ^6LiF - ^7LiF TLDs in the form of extruded Teflon matrix chips were placed at the center of each spherical moderator. Incident neutrons are thermalized as they interact with the spheres via elastic and/or inelastic scattering. Neutrons are detected through the (n,α) reaction with ^6Li , which has a cross section of 950 barns at thermal energies. Since ^6LiF is also sensitive to photons, ^7LiF was used to estimate the ^6LiF response to photons. Hence, the net neutron response of ^6LiF can be obtained. The moderating spheres are

composed of polyethylene (density = 0.95 g/cc), with diameters of 2, 3, 5, 8, 10, and 12 inches.

3.2 TLD CALIBRATION

A Teflon matrix containing the TLD powder made by Teledyne¹ are the type of TLDs used here. These TLDs were made in the shape of solid discs 11.2 mm in diameter, and a thickness of 0.4 mm for the ^6LiF , and discs of 12.7 mm in diameter, and a thickness of 0.44 mm for the ^7LiF . A set of fifty ^6LiF chips and another set of fifty ^7LiF chips were used. The TLDs were read with a TLD reader at the Stanford Linear Accelerator Center (SLAC) dosimetry laboratory. The thermoluminescent light (TL) output of the TLD reader was in units of volts. Because the light output is expressed in terms of the photomultiplier output, the stability of the TLD counting system was maintained with a ^{14}C light source. After calibration, the two sets of TLD chips were divided into groups of four. A pair of ^6LiF chips and a pair of ^7LiF chips selected at random from these sets were sealed in a plastic packet and marked for irradiation. An identification number is printed on each chip for tracking and control.

The individual sensitivity for every TLD chip was obtained from irradiation to a NIST traceable ^{60}Co gamma source at the calibration facility at SLAC. The absolute sensitivity of the BSS with TLDs was calibrated using a NIST traceable ^{252}Cf neutron source. A description of the above calibration procedures and a discussion of the results can be found in the radioisotopic portion of this study [6].

¹ Teledyne Isotopes, 50 Van Buren Avenue, Westwood, NJ, 07675

3.3 EXPERIMENTAL SETUP

The irradiation locations around the accelerator for the BSS are identical to positions A, B, and C used with the BDS and presented in Figure 1.1 of chapter I. Position D, located above the accelerator, was not measured due to the difficulty for safe operation and accurate setup.

Bonner sphere measurements at the three locations, for each accelerator, were completed in one session. These measurements were made at the completion of manufacturing and calibration at the Varian plant for the 10, 18, and 20 MV machines. The 15 MV measurements were made at the customer's site during acceptance testing of the LINAC. The 15 MV accelerator measurements included position D, which was accomplished by rotating the gantry by 90 degrees. Therefore, position D data using the BSS for the 15 MV accelerator is not done for the standard gantry location used for the other measurements with respect to ceiling and walls. The treatment room at which the 15 MV accelerator was measured was smaller in surface area than the test cells at Varian, but typical for hospital based facilities. Aluminum tripods with rings of different sizes at the top were used to hold the spheres in position. The vertical position of each tripod assembly is adjusted using a mechanical lift with a platform on which the tripods are placed, so that the center of each sphere would be at the desired height. Since the distances between measurement positions are large enough (greater than 50 cm), it was possible to perform two measurements with different detectors simultaneously. For example, while the 2 inch sphere is being irradiated at position A, the 3 inch sphere is irradiated simultaneously at Position C. Since they are separated by more than 1 meter, they had very little or no effect on each other.

A plastic packet containing the four TLD chips was used with each of the six moderating spheres at each measurement position for each machine. In addition, two measurements using bare and cadmium-covered TLD pairs were also made at all of these positions. The order of the measurements and sphere sizes were randomly selected. The last two chips from each set were used to determine the background.

The irradiation time was set such that good statistics for the TLD responses were achieved. This time was a function of the accelerator energy; the higher the accelerator energy the lower the photon dose needed to obtain satisfactory readings on the TLD. The total photon dose delivered ranged between 40 Gy (4000 rads) for the 20 MV machine to 150 Gy for the 10 MV machine. After the irradiation of each sphere, the corresponding TLDs were removed and labeled (for accelerator energy, photon dose delivered, and location of measurement). Reading of the TLDs was accomplished within 24 hours after irradiation, and took about 45 seconds per chip. The stability of the reader response was monitored after 10 chips were read and the high voltage power supply was adjusted, if needed, to give the same light output from the ^{14}C light source.

3.4 DATA ANALYSIS

The signals of the ^7LiF chips were used to measure the gamma response of their paired ^6LiF chips. The net neutron response of the ^6LiF is then used as input to the BUNKI unfolding code in order to derive the neutron fluence and dose equivalent. Because the response of each chip is different, two chips of each TLD type were used, and their responses were averaged before use in the

spectral analysis. After reading the irradiated TLD chips, an average response of the net neutron signal was obtained for each sphere at each irradiation position as follows:

- 1) the ^{60}Co calibration readings from all ^7LiF TLDs were averaged and called (Mean₇).
- 2) Mean₆ was obtained as in (1) for all ^6LiF TLDs.
- 3) the calibration reading (RC^7 and RC^6 in volts) for each chip from the exposure to ^{60}Co source was divided by the proper mean value, with the resulting term referred to as the effective calibration factor ($\text{ECF}^7 = \text{RC}^7/\text{Mean}_7$ and $\text{ECF}^6 = \text{RC}^6/\text{Mean}_6$).
- 4) the exposure reading (R^6 and R^7) from each chip resulting from exposure to the accelerator photon-neutron field is then divided by the effective calibration factors obtained in step (3) and from it a background reading is subtracted to obtain a value representing the corrected total signal ($S^{6(n+\gamma)}$ for ^6LiF chips, and $S^7(\gamma)$ for ^7LiF chips) for each TLD.
- 5) since there were two chips of each type for each position, the corrected signals for the two ^7LiF chips were averaged and called D_γ .
- 6) the net neutron signal, $S^6(n)$, from the ^6LiF TLDs was obtained using:

$$S^6(n) = S^{6(n+\gamma)} - D_\gamma \cdot \frac{\text{Mean}_6}{\text{Mean}_7}$$

The net $S^6(n)$ was then normalized to the delivered dose. This normalized response is then used as input into the BUNKI unfolding code. The value ($D_\gamma \times \text{Mean}_6/\text{Mean}_7$) in the above equation represents the response of the ^6LiF TLDs to the gamma radiation in the mixed field of the accelerator.

The $S^6(n)$ responses are plotted as the normalized response versus sphere diameter by position for each accelerator in Figures 3.1 through 3.4. From these

figures we can assess the response of the BSS to accelerator energy and measurement positions, and observe any abnormality in these responses.

An examination of Figures 3.1 through 3.4 reveals no abnormalities and indicates a trend. Generally, the response (net neutron signal in volts per photon Gy) versus sphere diameter peaks at a sphere diameter of 5 inches and falls off as the sphere diameter increases. The magnitude of the response increases as the accelerator energy increases. The TLD responses of the four accelerators show position A (40 cm from isocenter and 107.7 cm from the target) has the greatest range of response. The net signal distribution in all the plots is quite broad and skewed, with position B (located 141.4 cm from the target) the most severe case. The 15 MV accelerator data shows positions C and D to have comparable responses, except for the 3 inch sphere, where the D position was higher by a nominal 40 percent. This can be explained by the fact that for the 15 MV LINAC positions C and D are almost the same with respect to the ceiling and walls, since the gantry was rotated 90 degrees to measure position D. Hence, the principal difference these positions have is the composition and/or thickness of treatment head shielding.

3.5 SPECTRA UNFOLDING USING BUNKI

The BSS, despite its physical difficulty to use, has been accepted as one of the better techniques for measuring neutron spectra. In order to yield neutron spectrum from the measured detector response data, a mathematical unfolding procedure is required. The following degenerate Fredholm integral equation of the first kind relates the detector counts, C_i , the detector response function, $\sigma_i(E)$, and the neutron spectrum, $\Phi(E)$, for a BSS of M detectors

Figure 3.1. The net neutron response in volts, of the ^6LiF TLDs, versus the Bonner sphere diameter in inches for the three positions for the 10 MV accelerator.

Figure 3.2. The net neutron response in volts, of the ^6LiF TLDs, versus the Bonner sphere diameter in inches for the four positions for the 15 MV accelerator.

Figure 3.3. The net neutron response in volts, of the ⁶LiF TLDs, versus the Bonner sphere diameter in inches for the three positions for the 18 MV accelerator.

Figure 3.4. The net neutron response in volts, of the ^6LiF TLDs, versus the Bonner sphere diameter in inches for the three positions for the 20 MV accelerator.

$$C_i = \int_{E_{min}}^{E_{max}} \sigma_i(E) \Phi(E) dE \quad (1)$$

where $i=1,2,3,...M$.

The response function $\sigma_i(E)$ is not known analytically for the BSS, so it has to be determined experimentally or calculated as discrete points. At that point, a solution for $\Phi(E)$ can be found using unfolding techniques [7][8].

Because the number of detectors (8 in our case) is less than the number of energy bins used to define the neutron spectrum (31 bins in this case), a unique solution to equation 1 cannot be found, and the task is then to find an approximate solution rather than an exact one. Choosing a physically acceptable approximate solution may lead to an appropriate solution by imposing additional constraints on the solution in equation 1 such as non-negativity conditions, smoothness, and general shape of the spectrum [7][9].

The BUNKI program was used as the unfolding technique in this study, with minor alterations for a plotting capability, and some arrays alterations to include responses for the BDS spectrometry set described in chapter II. BUNKI includes a modification to the SPUNIT method by Doroshenko or BON31G by Sanna [10].

It is a well known fact that the results obtained by most unfolding codes, including BUNKI, depend on the initial guess of the solution. Since the initial guess has a great impact on the final solution, BUNKI incorporated an algorithm, MAXIET, made up of a Maxwellian shape (MAX) of the high energy component, a $1/E$ component (IE), and a thermal component (T). Several trials were made with other choices, but MAXIET seemed to give the most appropriate results of the well-characterized ^{252}Cf spectrum. The BUNKI code input parameters were optimized during detector calibration with the ^{252}Cf neutron source at SLAC.

The result of the calibration and a discussion of the methods are presented in the radioisotopic portion of this study [6]. The optimized input parameters were then used with the BUNKI code along with the TLD exposure data from around the accelerators. Figures 3.5 through 3.7 represent the BUNKI unfolded neutron spectra at the specified positions for the 18 MV produced by BUNKI. Examination of these plots reveals that they all have one peak, unlike the BDS results (two peaks). Additionally, the spectra peak at 0.1-0.3 MeV, and indicate positional dependence. BUNKI also calculates the total fluence, dose, dose equivalent, average energy (less thermal), and quality factors.

3.6 DISCUSSION

The results of the spectra unfolding using BUNKI are summarized in tables 3.1 through 3.4. Table 3.1 is a summary by accelerator energy and measurement positions of the neutron fluence. As can be seen from table 3.1, the fluence increases as the accelerator energy increases. The total fluence, for each machine, indicates dependence on measurement position relative to the target. Position A always has the highest fluence, while position B is the lowest. Table 3.2 is a summary of the neutron dose at each position, and table 3.3 represents the dose equivalent values. The dose equivalent values obtained also reflect the increase in accelerator energy, and exhibit positional dependence.

As exhibited by the average energy data, Table 3.4, there is no apparent pattern associated with the average energy values as a function of accelerator energy, or as a function of position. The 18 MV machine had the highest average energy for position A and B; all other machines are within a standard deviation of each other. The average energy for position B for the 10 MV machine showed

Figure 3.5. The 18 MV accelerator neutron spectra at position A, using the BSS system. The plot is the neutron fluence [cm^{-2}] per unit lethargy versus neutron energy [MeV]. Digital data are presented in tables in appendix B.

Figure 3.6. The 18 MV accelerator neutron spectra at position B, using the BSS system. The plot is the neutron fluence [cm^{-2}] per unit lethargy versus neutron energy [MeV]. Digital data are presented in tables in appendix B.

Figure 3.7. The 18 MV accelerator neutron spectra at position C, using the BSS system. The plot is the neutron fluence [cm^{-2}] per unit lethargy versus neutron energy [MeV]. Digital data are presented in tables in appendix B.

an unusually low value, which may indicate an experimental error. The fluence-to-dose-equivalent factors utilized by the BUNKI code are presented in table 3.5. Quality factors are summarized in table 3.6; they are comparable to those obtained with BDS-BUNKI.

Table 3.1

Total neutron fluence [$\text{cm}^{-2} \text{Gy}^{-1}$] measured by the BSS, using BUNKI unfolding method.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	2.43E+05	1.63E+05	2.10E+05	N/A
15 MV	5.34E+06	3.02E+06	4.08E+06	4.97E+06
18 MV	7.72E+06	5.61E+06	6.34E+06	N/A
20 MV	1.14E+07	7.54E+06	9.99E+06	N/A

Table 3.2

Dose [Gy Gy^{-1}] measured by the BSS, using BUNKI unfolding method.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	2.85E-06	1.08E-06	2.12E-06	N/A
15 MV	5.49E-05	3.62E-05	4.71E-05	5.61E-05
18 MV	1.06E-04	7.30E-05	8.24E-05	N/A
20 MV	1.42E-04	7.87E-05	1.33E-04	N/A

Table 3.3

Neutron dose equivalent [Sv Gy^{-1}] measured by the BSS, using BUNKI unfolding method.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	2.26E-05	4.83E-06	1.55E-05	N/A
15 MV	4.14E-04	2.68E-04	3.58E-04	4.32E-04
18 MV	8.83E-04	5.60E-04	7.12E-04	N/A
20 MV	1.19E-03	6.05E-04	1.12E-03	N/A

Table 3.4

Average neutron energy [MeV] measured by the BSS, using BUNKI unfolding method.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	0.28	0.043	0.19	N/A
15 MV	0.19	0.37	0.27	0.25
18 MV	0.42	0.45	0.30	N/A
20 MV	0.29	0.19	0.35	N/A

Table 3.5

Fluence-to-Dose-Equivalent Conversion Factors [Sv cm^2] measured by the BSS, using BUNKI unfolding method.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	9.32E-11	2.96E-11	7.38E-11	N/A
15 MV	7.75E-11	8.87E-11	8.77E-11	8.69E-11
18 MV	1.14E-10	9.98E-11	1.12E-10	N/A
20 MV	1.04E-10	8.02E-11	1.12E-10	N/A

Table 3.6

Quality factors measured by the BSS, using BUNKI unfolding method.

Position⇒ Energy↓	Position A	Position B	Position C	Position D
10 MV	7.9	4.5	7.3	N/A
15 MV	7.5	7.4	7.6	7.7
18 MV	8.3	7.7	8.6	N/A
20 MV	8.4	7.7	8.5	N/A

There is an error index associated with each BUNKI output, which is a measure of the degree of variation between experimentally measured responses using the detectors, and the responses calculated by the BUNKI code using the detector response matrix. This fitting error index ranged from a minimum of less than 1 percent to nominally 8 percent for most cases. The BUNKI fitting error for position B for the 10 MV machine was 24 percent, which may explain the relatively low average energy value. The input data for the BUNKI code allows one to enter a value for the experimental percent error of the sphere responses based on counting statistics, sphere positioning errors, and other recurring errors. It is very convoluted to exactly determine the total error associated with the measurements and the unfolding process. Based on some benchmark measurements performed with a ^{252}Cf neutron source, such an error ranged between 15 percent for the 2 inch sphere and 2 percent for the 12 inch sphere. However, the following method was used to estimate the error associated with the unfolding results. To test the sensitivity of the BUNKI code to the input values, these input values were randomly changed by as much ± 10 percent and

the BUNKI outputs were evaluated. Ten sets of randomly changed sphere responses were used as input. Average value and standard deviation for the ten outputs were subsequently calculated. The standard deviation of these output was about 13 percent. This result indicates that the values calculated by the BUNKI unfolding code to be conforming and very reasonable.

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CHAPTER IV

FOIL ACTIVATION

4.1 INTRODUCTION

Foil activation as a mean for detecting neutrons is a well understood technique which is based on the creation of a radionuclide via neutron capture and the counting of the resulting radiation emission from the decaying radionuclide. The choice of foil depends on the type of field being measured. Gold and indium foils are the preferred choice of foils for measuring thermal neutrons because of the high thermal capture cross section of these two elements. Either beta or gamma spectroscopy techniques can be used to measure the induced activity. Gold has a longer half-life ($t_{1/2} = 2.7$ days) than indium ($t_{1/2} = 54$ minute), but indium has a higher thermal cross section than gold ($\sigma_{In} = 202$ barns, $\sigma_{Au} = 99$ barns).

The use of foil activation to measure thermal fluence has several advantages: foils can be very small, hence they will not perturb the neutron fluence. They are effectively insensitive to photons with energies typical of the leakage environment around medical LINACs. They are passive detectors, so the pulsed field nature of the accelerator has no effect on them. They can be placed anywhere in the room, and are not affected by environmental conditions (i.e. temperature, humidity, or pressure changes).

In this study, the epithermal and fast neutron components inside the cell housing the accelerator were measured by the activation of moderated indium foils, based on the reaction:

The activity induced in the foil is measured by a computer controlled Geiger counting station, for detection of the β radiation.

4.2 EXPERIMENTAL SETUP

Two types of moderators were employed with the indium foils in this study: a fluence moderator was used to measure the neutron fluence and an Anderson-Braun (A-B) type remmeter was used to measure dose equivalent. The fluence moderator is a cylindrical plug of polyethylene 15.70 cm in diameter and 14.80 cm in height wrapped in 0.32 cm of 25 weight-percent boron uniformly distributed throughout a silicone elastomer sheet¹, all housed in an ABS plastic cover 0.50 cm thick. The fluence moderator is designed to measure the fast neutron fluence in the field with a response relatively independent of the incident neutron energy. The purpose of the boron sheath is to absorb the incident thermal neutrons. Stephens and Smith showed that the response of a similar type moderator, with different energy neutron sources, was relatively insensitive to neutron energy in the range 20 keV to 20 MeV [1].

The A-B type remmeter was an NRC² Snoopy with BF₃ tube, specially modified to be used with foils to specifically measure the neutron dose equivalent in the vicinity of LINACs. The modification consisted of removing the BF₃ tube and replacing it with an indium foil reproducibly supported at the center of the detector by a simple polyethylene fixture [2]. Since the energy

¹ Reactor experiments, INC. 1275 Hammerwood Avenue, Sunnyvale, California, U.S.A., 94089.

² Nuclear Research Corporation, 125 Titus Avenue, Warrington, PA, 18975.

response of the remmeter is tailored to be close to the fluence-to-dose equivalent conversion factor curve, it can be used to measure the neutron dose equivalent directly. The dose equivalent response of the remmeter was described by the designers as uniform in the energy range from thermal to 10 MeV [3]. The fluence moderator's measured fluence, and the remmeter measured dose equivalent can be used together to obtain the average energy of the neutron spectrum from the response ratio of the two terms. Additionally, the absorbed dose can be obtained by using the quality factors defined by the knowledge of the former parameters.

Due to the small size of the fluence moderators, several of them were used to measure several positions simultaneously, without risk of perturbing the neutron fluence for the adjacent locations. The foils (2.54 cm in diameter and 0.0127 cm thick with 0.0127 cm thick aluminum packing) were placed at the geometric center of the moderators, which in turn, were positioned at standard locations around the accelerator. Figure 4.1 shows the 13 locations at which measurements were performed with the fluence moderators and the remmeter, with a coordinate system convention based on an International Electrotechnical Commission (IEC) draft standard [4]. The IEC Cartesian coordinate system uses x_f , y_f , and z_f to identify measurement locations. Table 4.1 summarizes these locations. The 1-13 position names in the table will be used throughout this chapter to refer to these locations. Position 1 in this chapter is the same as position D for the BDS system (chapter II) and the BSS system (chapter III). Similarly, position 3 corresponds to position C, position 10 corresponds to position A, and position 11 corresponds to position B.

Figure 4.1. Presentation of the measurement positions for the fluence moderator and the remmeter. Positions 1 through 13 are explained in the text. The accelerator's isocenter is the origin of the coordinate system.

Table 4.1

Positions around the accelerator head at which measurements using the fluence moderators and remmeter were performed. A simple numerical position name was used for convenience. It also shows the position at which measurements using other methods were performed.

Position (x_f, y_f, z_f) IEC designation, IEC reference [4]	Position name	Position name used elsewhere
0.0, 0.0, 2.0	1	D
0.0, 1.0, 1.0	2	
-1.0, 0.0, 1.0	3	C
0.0, -1.0, 1.0	4	
0.0, 0.0, 0.0	5	
0.4, 0.0, 0.0	6	
1.0, 0.0, 0.0	7	
0.0, 0.4, 0.0	8	
0.0, 1.0, 0.0	9	
-0.4, 0.0, 0.0	10	A
-1.0, 0.0, 0.0	11	B
0.0, -0.4, 0.0	12	
0.0, -1.0, 0.0	13	

All positions in the patient plane ($z_f = 0$ m) were made by placing the detectors atop a 20 cm wide by 400 cm long by 5 cm thick wood platform. Measurements in the target plane ($z_f = 1$ m) were performed by positioning the detectors on an aluminum shims on the level step of a ladder. Measurements above the target ($z_f = 2$ m) were made by suspending the detectors from a ceiling crane with a rope. The same setup was used for all four accelerators.

After the placement of the foils inside the moderators, the accelerator x-ray dose rate (Gy min^{-1}) is set at maximum in order to deliver a pre-determined

photon dose (Gy) in the shortest time. Photon dose is defined as the total x-rays delivered to a water phantom at D_{max} (distance of maximum dose) for a 10 x 10 cm field at 100 cm TSD (target to phantom surface distance). Enough total dose was delivered to each foil to achieve 1% or less counting statistics (at least 10000 counts) for each foil at each position. To achieve relatively equivalent counting rates, positions require different doses depending on their distance from the target, which type of moderator was used, and the energy of the LINAC. All measurements were done with the collimator jaws of the accelerators in the closed position (primary beam intercepted) and the gantry in an upright position and stationary.

4.2.1 Board Corrections

As previously mentioned, a wooden board was used to support the moderators during irradiation. To account for the effect of this board on the response of the detectors, an experiment was performed to quantify this effect. Positions 1,2,3, and 4 need no correction, because no board was used. For the other positions, two sets of measurements with each moderator were taken. The first set of measurements was made with the normal setup (i.e., the board was in place and detectors were positioned upon it). The second set of measurements was performed with the board removed and the detectors suspended at the desired location with a rope attached to a ceiling crane. The neutron fluence and dose equivalent from these two sets of measurements were calculated as before. A correction factor was derived for each moderator and each measurement position where the board was used. This correction factor ranged between 0 and 7 percent of the measured fluence and dose equivalent. The board was

employed because it was easier for repeated measurements, and detector positioning was more readily reproducible.

4.2.2 Counting of Foil Activity

After irradiation, the indium foils were counted on a G-M counting station. The indium foil discs are permanently affixed to an equivalent diameter aluminum disc, for structural support. Since the thermal capture product of aluminum is ^{28}Al , the aluminum does not present a problem as the relatively small cross section, and the short half-life (2.24 minutes) facilitates decay to insignificant levels prior to the counting ^{116}In [5]. Other products from aluminum include ^{26}Al and $^{26\text{m}}\text{Al}$ via (γ, n) reactions, but they have an extremely small cross sections and a very long half-life (7×10^5 y) for ^{26}Al , and a very short half-life (6.34 s) for $^{26\text{m}}\text{Al}$ [5]. Typically, a wait time of 30-60 minutes passed before counting the foils, rendering the aluminum activation contribution negligible. The counting was performed with a thin-window Geiger tube 2.54 cm in diameter with an end-window thickness of 1.4 mg cm^{-2} , coupled to a Ludlum³ Model 2200 portable scalar rate meter, and a desktop computer.

The counting setup was lead shielded and typically had a background count rate of about 7 cpm. The stability of the setup was checked against an uranium disk source prior to any foil counting. The indium foils are positioned on shelves of varying distance from the detector window. The optimum shelf location for each foil was set to get approximately 2000 to 10000 counts per minute (cpm), in order to minimize the electronics dead time and counting errors. During data analysis a correction factor corresponding to each shelf's

³ Ludlum Measurements, INC., PO BOX 810, Sweetwater, TX, 79556.

relative efficiency was applied to the measured counts normalized to the top shelf (closest to the detector). For multi-foil irradiations, foils which were positioned the farthest from isocenter during irradiation were counted first, because they would have the lowest activities of the batch being irradiated together. The entire counting station was connected to a personal computer to enable automation and data storage for later analysis.

4.2.3 Equipment Calibration

A complete description of the procedure and the results of calibrating the detectors and counting equipment using the SLAC ^{252}Cf neutron source is published in the first part of this work [6]. The calibration factor obtained for the fluence moderator was $0.775 \text{ cm}^{-2} \text{ cpm}^{-1}$ at saturation count rate. The calibration factor obtained for the remmeter was $8.33 \times 10^{-10} \text{ Sv cpm}^{-1}$ at saturation count rate. Both calibration factors were obtained using an indium foil counted on the top shelf.

4.3 DATA ANALYSIS

With the described setup and the calibration factors obtained above, determination of the neutron fluence is possible from the measurements of the induced activities in the moderated foils placed in the radiation field. The amount of induced activity depends upon several factors: the activation cross section of the foil material (indium), the number of ^{115}In atoms in the foil, the neutron fluence, the irradiation time, the time elapsed between irradiation and counting, and the counting time of the induced activity [7]. The saturation count rate is calculated from measured data to correct for the irradiation time, elapsed

time, and the counting time of the induced activity, all at once. The saturation count rate is the maximum count rate that can be induced in an indium foil by the neutron fluence rate of the measured neutron field. The measured count rate, C , can be related to the saturation count rate, C_s , by the following equation

$$C_s = \frac{C \lambda t_c \exp(\lambda t_w)}{(1 - \exp(-\lambda t_i)) (1 - \exp(-\lambda t_c))} \quad (1)$$

where:

λ = the decay constant for ^{116}In ($2.13\text{E-}04 \text{ s}^{-1}$).

t_i = the irradiation time.

t_w = elapsed time from end of irradiation.

t_c = the counting time.

The saturation count rate is then used with the appropriate calibration factor to calculate the neutron fluence from the fluence moderator measurement; dose equivalent from the remmeter measurement; average energy from both detectors measurements; and, the quality factor for each position.

4.3.1 Neutron Fluence Calculations

As previously indicated, all the detectors and equipment used in the measurement of the neutron field around the accelerators were calibrated to evaluate their response to a known ^{252}Cf neutron source spectrum and fluence rate [6]. To obtain the neutron fluence rate measured by the fluence moderator, the fluence moderator calibration factor discussed above, is multiplied with the saturation count rate. Table 4.2, presents the measured neutron fluence per position for the four accelerators.

Table 4.2

Fast neutron fluence [$\text{cm}^{-2} \text{Gy}^{-1}$] measured using the moderated indium foil activation with the fluence moderator. Data are normalized per unit x-ray dose output.

X-ray energy⇒	10 MV	15 MV	18 MV	20 MV
Position⇓				
1 (D)	2.17E+05	3.16E+06	7.09E+06	8.67E+06
2	3.02E+05	4.42E+06	9.48E+06	1.16E+07
3 (C)	1.88E+05	2.48E+06	5.75E+06	7.65E+06
4	3.22E+05	4.44E+06	1.00E+07	1.18E+07
5	2.78E+05	3.74E+06	6.45E+06	8.66E+06
6	2.51E+05	3.28E+06	7.97E+06	8.83E+06
7	1.83E+05	2.47E+06	5.52E+06	6.68E+06
8	1.90E+05	3.04E+06	7.21E+06	6.95E+06
9	1.21E+05	2.08E+06	4.62E+06	5.17E+06
10 (A)	2.16E+05	3.05E+06	7.41E+06	7.83E+06
11 (B)	1.32E+05	2.08E+06	4.77E+06	5.05E+06
12	1.90E+05	3.21E+06	7.12E+06	6.98E+06
13	1.27E+05	2.34E+06	4.90E+06	4.88E+06

4.3.2 Scattering Corrections

Correction of the neutron fluence may be applied to account for the scattering contribution from the room walls. From a series of MORSE calculations McCall *et al.*[8] found that the fluence from the wall scatter contribution is proportional to the inside surface area of the concrete cell in which measurements are being performed. This scatter component was also found to be constant throughout the cell, and the scatter fluence, ϕ_{SC} , was found

from a formula similar to that for thermal neutrons discovered by Patterson and Wallace [9], i.e.,

$$\phi_{sc} = \frac{kQ}{S} \quad (2)$$

where Q is the fast neutron source strength, S is the inside surface area of the measurement room in cm^2 , and k is a constant found to be 4.6 for tungsten shielded accelerators and 5.4 for lead shielded accelerators [10]. Equation (2) was used to obtain values for the scattered component of the fluence for the four accelerators presented in Table 4.3.

Table 4.3

Scattered neutron fluence [$\text{cm}^{-2} \text{Gy}^{-1}$] calculated using equation 2 discussed in the text above.

Accelerator energy	$\phi_{sc} (\text{cm}^{-2} \text{Gy}^{-1})$
10 MV	3.34E+05
15 MV	4.91E+06
18 MV	9.41E+06
20 MV	1.21E+07

4.3.3 Dose Equivalent Calculations

The dose equivalent rate measured by the A-B remmeter is found by the product of the remmeter calibration factor and the measured saturation count rate. The measured dose equivalent values per unit photon dose delivered for

the four machines are presented in Table 4.4. Table 4.5 presents a tabulation of the quality factors at each of the points of measurements. Quality Factors are conversion factors obtained using Figure 31b divided by conversion factors obtained using Figure 31a of NCRP-79.

Table 4.4

Neutron dose Equivalent [Sv Gy^{-1}] as measured using the moderated indium foil activation method with the Anderson-Braun moderator. Data are normalized per unit dose.

X-ray energy⇒	10 MV	15 MV	18 MV	20 MV
Position⇓				
1 (D)	2.67E-05	5.07E-04	1.21E-03	1.45E-03
2	4.35E-05	7.98E-04	1.74E-03	2.20E-03
3 (C)	2.61E-05	4.40E-04	9.68E-04	1.25E-03
4	4.73E-05	8.77E-04	1.91E-03	2.20E-03
5	3.99E-05	6.74E-04	1.46E-03	1.87E-03
6	4.10E-05	6.26E-04	1.53E-03	1.67E-03
7	2.72E-05	4.55E-04	1.07E-03	1.31E-03
8	3.02E-05	5.87E-04	1.38E-03	1.28E-03
9	2.06E-05	3.96E-04	9.46E-04	9.24E-04
10 (A)	3.56E-05	5.94E-04	1.50E-03	1.52E-03
11 (B)	2.05E-05	4.13E-04	9.10E-04	9.77E-04
12	3.10E-05	5.94E-04	1.48E-03	1.31E-03
13	1.99E-05	4.50E-04	9.45E-04	9.59E-04

Table 4.5

Quality Factors obtained by moderated indium foil activation method with the fluence moderator and the A-B remmeter.

X-ray energy⇒	10 MV	15 MV	18 MV	20 MV
Position⇓				
1 (D)	8.4	9.1	9.3	9.3
2	8.8	9.5	9.6	9.7
3 (C)	8.7	9.5	9.3	9.2
4	8.9	9.8	9.7	9.6
5	8.8	9.5	10.2	10.1
6	9.2	9.7	9.7	9.6
7	8.9	9.6	9.7	9.8
8	9.1	9.7	9.7	9.6
9	9.3	9.7	9.9	9.5
10 (A)	9.2	9.7	9.9	9.7
11 (B)	9.1	9.8	9.7	9.7
12	9.2	9.6	9.9	9.6
13	9.1	9.7	9.7	9.8

4.3.4 Average Energy Calculations

McCall, Jenkins and Shore developed a cook-book approach to obtaining the fluence-to-dose equivalent conversion factors given the average energy of the spectra [8]. The results of performing many MORSE calculations using known spectra and some monoenergetic neutrons were made into a plot of fluence-to-dose equivalent conversion factors versus average neutron energy. This plot is Figure 31a of the NCRP report number 79 [10]. Figure 31a was used here in a reverse fashion. We measured the neutron fluence using the fluence moderators, and the neutron dose equivalent using the remmeter. From the ratio of these two

type of measurements, we obtain a fluence-to-dose equivalent conversion factor. This measured conversion factor together with Figure 31a of NCRP-79 were used to obtain the average energy. Table 4.6 presents the results for the average energy from these calculations.

The average energy, $\bar{E}_{\text{dir}}$, using McCall's cook-book method, is presented in Table 4.7. The scattered neutrons average energy component was found to be related to the direct component by the following relationship:

$$E_{\text{sc}} = 0.24 \bar{E}_{\text{dir}} \quad (3)$$

where $\bar{E}_{\text{dir}}$ is the average energy of the direct neutron spectrum only (total minus scatter). The total neutron spectrum average energy (direct and scatter) is related to the direct average energy as follows:

$$\bar{E} = \bar{E}_{\text{dir}} \left(1 - \frac{4.1 \times 4\pi R^2}{S + 5.4 \times 4\pi R^2} \right) \quad (4)$$

where R is the distance from the target to the measurement position, and S is the surface area of the concrete room. Scattered neutrons average energy calculated based on equations (3) and (4), is presented in Table 4.8.

4.3.5 Transport of Neutrons in the Head

The geometry of the material used for shielding the head of a medical LINAC is very complex. This shielding is never a perfect, solid shape such as spheres or cubes, due to the numerous movable and fixed parts of the treatment head. Since the primary purpose of the shielding is to shield against photons, high atomic number materials are used, such as tungsten and lead.

Table 4.6

Neutron average energy measured using indium foil activation method.

X-ray energy⇒ Position↓	10 MV	15 MV	18 MV	20 MV
1 (D)	0.43	0.62	0.67	0.66
2	0.54	0.73	0.75	0.78
3 (C)	0.51	0.72	0.66	0.64
4	0.55	0.83	0.79	0.77
5	0.54	0.73	1.00	0.93
6	0.64	0.79	0.79	0.78
7	0.56	0.75	0.80	0.82
8	0.62	0.80	0.79	0.75
9	0.67	0.78	0.87	0.72
10 (A)	0.65	0.81	0.86	0.81
11 (B)	0.60	0.83	0.79	0.80
12	0.64	0.76	0.88	0.77
13	0.61	0.80	0.80	0.82

Table 4.7

Neutron average energy, $\bar{E}_{dir}$, calculated using McCall's cook-book method as illustrated in NCRP-79.

X-ray energy⇒ Position↓	10 MV	15 MV	18 MV	20 MV
1 (D)	0.54	0.75	0.80	0.80
2	0.67	0.89	0.89	0.94
3 (C)	0.63	0.87	0.79	0.77
4	0.68	1.00	0.94	0.92
5	0.66	0.88	1.19	1.12
6	0.82	0.98	0.97	0.96
7	0.81	1.05	1.09	1.13
8	0.79	1.00	0.96	0.93
9	0.97	1.09	1.18	1.00
10 (A)	0.82	1.01	1.04	0.99
11 (B)	0.86	1.16	1.07	1.11
12	0.81	0.94	1.08	0.94
13	0.88	1.11	1.08	1.13

Table 4.8

Scattered neutron average energy [MeV] calculated utilizing McCall's cookbook method as described in NCRP-79. The average energy of scattered neutron,

$$\bar{E}_{sc} = 0.24 * \bar{E}_{dir} .$$

X-ray energy⇒	10 MV	15 MV	18 MV	20 MV
Position⇓				
1 (D)	0.13	0.18	0.19	0.19
2	0.16	0.21	0.21	0.22
3 (C)	0.15	0.21	0.19	0.18
4	0.16	0.24	0.23	0.22
5	0.16	0.21	0.29	0.27
6	0.20	0.23	0.23	0.23
7	0.20	0.25	0.26	0.27
8	0.19	0.24	0.23	0.22
9	0.23	0.26	0.28	0.24
10 (A)	0.20	0.24	0.25	0.24
11 (B)	0.21	0.28	0.26	0.27
12	0.19	0.23	0.26	0.23
13	0.21	0.27	0.26	0.27

Other materials that may be present in the treatment head and used for various reasons are mentioned in chapter I. McCall did a study using Monte Carlo techniques to find the average energy of various spectra and the dose equivalent as a function of the shield thickness. The results show an exponential decrease in the energy with increase in the shielding thickness [8]. In his calculations, McCall assumed a spherical shape for an all lead, or an all tungsten shield. McCall showed that the average energy decrease in an all tungsten shield is

much greater than that in lead. This can be seen in Figures 27 and 28 of NCRP-79 [10].

In our study, a detailed drawing of the accelerator head (except for the target, and flattening filters, the head designs are identical for the 15, 18, 20 MV LINACs) was produced and measurements were made to determine the thicknesses and types of all of the materials between the target and each point of measurement. In his study [8], McCall compiled enough data to devise a method to show the magnitude of decrease of average energy with shielding thickness. This method was presented as a semi-log graph of Half Energy Layers (HEL) in cm versus the average energy in MeV for three different materials: tungsten, lead, and iron, as shown in Figure 29 of NCRP-79 [10]. The half energy layer is defined as the thickness of material which decreases the average neutron energy by a factor of two.

The calculations used here are based on the data from the graph of HEL versus average energy taken from McCall's original Monte Carlo calculations. In our calculations, materials such as steel and copper were treated as iron, since they have a similar inelastic cross section, and thereby have a similar effect on neutrons [5]. McCall also calculated the bare target average neutron energy, which he calls the primary average energy (E_{pri}). This average energy is that of the initial undegraded spectra, i.e., the spectra resulting from the photoneutron production from the target material without shielding. These spectra were obtained, using Monte Carlo methods, by bombarding a tungsten or lead target with several electron energies. Average energies from these spectra, as well as monoenergetic neutron source terms were used to generate the HEL graph of NCRP-79. The spectra used by McCall to generate the HEL values are given as

Table 8 in NCRP-79 [10]. In the medical LINACs used in this study, 3 to 4 different materials collectively comprise the construction of the electron target and the beam flattener which are the major sources of neutrons in the treatment head.

Primary average energies from the McCall calculations were used as the starting average energy of the neutron spectrum for a particular electron energy and target material. The effect of each shielding layer on the average neutron energy was determined using the Half Energy Layer method, and the process was repeated for each material in the shielding matrix obtained from the treatment head drawing. The original data points for the HEL values were extracted from the original graph provided by McCall, and were fitted by a power function for each of the three materials. The derived equation for half energy layers as a function of average energy is used in the iterative calculation described below. These fitted equations, as a function of neutron average energy in MeV, for the three materials considered were as follow: for tungsten, $HEL = 10.7(E)^{-0.615}$, for iron, $HEL = 18.7(E)^{-0.664}$, and for lead, $HEL = 60.2(E)^{-1.391}$. These equations are derived for the neutron average energy in the range $0.1 < E \leq 2.5$ MeV. The following steps illustrate the HEL method.

- 1) Determine the primary average energy (E_{pri}) for the medical LINAC electron energy.
- 2) Determine all materials, and their thicknesses, in the path of the neutron source (i.e. target) from LINAC treatment head design drawings.
- 3) Determine the HEL for the first material in the matrix from McCall's graph of HEL versus Average Energy.

4) Determine the effect of the first material layer on average energy using E_{pri} of step (1) as the starting average energy. The effect of the first layer on the neutron average energy will be:

$$\bar{E}_{dir} = E_{pri} \times (0.5)^{\frac{t}{HEL}} \quad (5)$$

where t is the thickness of the material in first layer, and HEL is the value from the graph corresponding to E_{pri} .

5) The average direct energy calculated in step (4) will be the new starting average energy for the second layer, and this layer's effect will be calculated as in step (4) with t being the thickness of this layer; and the HEL is obtained from the graph for that average energy and material.

6) Repeat steps (4) and (5) until the last layer is reached, and the resulting average energy will be the final average direct energy.

Table 4.9 gives the results of these calculations for the average direct energy using the Half-Energy-Layer method.

4.3.6 Photoneutron Production in Detector Material

When trying to measure the neutron spectra around high energy medical LINACs, there is the problem of measuring neutrons in the presence of an intense photon field. Photoneutron production in the detector material may occur via (γ, n) reactions. Photoneutrons can be produced in the detector's thermal neutron shield, the polyethylene moderator, and the detector foil (indium in this case). In each element photoneutron production will exhibit a different threshold energy and cross section shape.

Table 4.9

Average direct energy ($\bar{E}_{\text{dir}}$) of neutrons as calculated using the Half Energy Layer (HEL) method.

X-ray energy⇒	10 MV	15 MV	18 MV	20 MV
Position⇓				
1 (D)	0.57	1.21	1.25	1.33
2	0.30	0.46	0.47	0.48
3 (C)	0.32	0.54	0.55	0.58
4	0.39	0.70	0.72	0.75
5	0.33	0.55	0.56	0.58
6	0.37	0.66	0.68	0.71
7	0.37	0.66	0.68	0.71
8	0.43	0.82	0.84	0.89
9	0.43	0.82	0.84	0.89
10 (A)	0.32	0.54	0.55	0.58
11 (B)	0.33	0.56	0.58	0.60
12	0.35	0.59	0.60	0.63
13	0.33	0.55	0.56	0.58

Therefore, each element must be accounted for separately and the results added to obtain a cumulative response. The photoneutron production from indium foils will present no problems for the following reasons: in the major isotope of indium, ^{115}In , the possible products are either very long-lived (50 d) and have no significant build up, or very short-lived (72 s) and decay away very quickly. In our measurements, we usually waited 30-60 minutes before counting the indium foils, allowing the decay of short-lived radionuclides to negligible levels.

In a SLAC publication, Jenkins, McCall, and Tochilin set out to measure and calculate the photoneutron response of a fluence moderator detector of the same design as used in this study, using Varian facilities and medical accelerators [11]. However, the fluence moderator used in the McCall *et. al.* study had a cadmium cover, while the fluence moderator used in this study had a boron cover. Two approaches were tried in the McCall study. The first was to measure the apparent neutron fluence by exposing a moderated indium foil one meter from the photon target. A comparison to the expected neutron fluence as determined by measurements of gold foil activation using the Patterson and Wallace methods was then made [9]. This approach revealed very little information other than the same order of magnitude for the neutron fluence was obtained.

The second approach was to separately measure each element's photon response, taking into account the different geometric efficiency for each element in the detector. The results of this study are summarized in Figure 4.2 [11]. The figure shows the apparent neutron fluence (cm^{-2}) per photon rad versus accelerator energy in MeV. This plot can be used to correct the measured neutron fluence for photoneutron responses. The application of this correction is straightforward. The experimenter simply looks up the apparent neutron fluence for the same peak energy on Figure 4.2, then subtracts that value from the measured neutron fluence per photon rad value to correct for the photon response in the detector.

It is obvious from Figure 4.2 that if a cadmium-covered detector is used, a correction may be needed. In our study, the detectors were boron-covered, and the photon energy was between 10 and 20 MV. It takes approximately 3.3 times

Figure 4.2. Apparent neutron fluence of the fluence moderators as measured by McCall. The curves labeled C, Cd and total represent the values for neutrons from the carbon (in the moderator), cadmium (in the shell) and the total, respectively [11].

as many boron atoms as cadmium atoms to yield the same thermal neutron shielding. Therefore, the neutron yield of the boron used, to achieve the same thermal neutron shielding, is approximated to be less than 5 percent that of cadmium in the energy range of our experiment [11]. However, the boron is in a rubber matrix in the form of boron carbide. It is a good approximation to treat this matrix as "carbon equivalent" and assign the yield the same energy dependence as carbon [12]. McCall did some measurements for Varian using both a cadmium cover and boron cover and found that the boron cover contributed only about 11 percent as many neutrons as the cadmium [12]. Hence, this adds 11 percent to the carbon response plotted in Figure 4.2. Clearly, the corrections are much smaller for boron covered detectors, and were neglected in the energy range of this experiment as the contribution is expected to be less than 1 percent of the measured total neutron fluence.

4.3.6 Measurement of Neutron Yield from Accelerators

The thermal neutron fluence yield from a fast neutron source placed inside a concrete walled cavity was found to be constant, as reported by Patterson and Wallace [9], and is given by a simple equation:

$$\phi_{th} = 1.25 Q/S \quad (6)$$

where;

- ϕ_{th} = thermal neutron fluence rate
- Q = number of neutrons per unit x-ray at isocenter
- S = inside surface area of the concrete room in cm^2

The 1.25 factor is an empirical constant. This equation assumes a spherical cavity and thick enough walls to allow for equilibrium.

The weakest part of the equation seems to be the 1.25 factor, which clearly depends on various physical assumptions and concrete formulations, and could vary from room to room depending on the concrete composition and age. McCall performed a measurement [13] to determine this constant. He used a 1 meter cubed cavity and a 1 inch diameter by 1 mil thick bare gold foil and received a thermal neutron calibration exposure from the National Bureau of Standards. He determined a value of 1.25 for the constant, and a cadmium ratio of 2.0. Equation 6 was used in this study. To make the measurement, bare indium foils were hung in mid-air on a piece of tape at least 1 meter from the walls and any other objects. The thermal fluence can be calculated using the measured saturated count rate and the foil's calibration factor. Since the McCall measurements were made with gold foils, and our study employed indium foils, a cross-calibration was performed. Gold and indium foils were irradiated under identical conditions with an 18 MV accelerator at Varian facilities to find this cross-calibration factor to be 0.73. This cross-calibration factor is the ratio of the bare indium foils saturation count rate, as measured during our experiment, to the bare gold foils thermal neutron fluence as measured by McCall and calculated based on the National Bureau of Standards calibration.

Measurement of the thermal neutron fluence, with bare indium foils, were made for each of the four LINAC energies investigated during the course of our study. Table 4.10 lists the thermal neutron fluence and the total photoneutron yield assessed for the four LINACs studied, as calculated using the data from the bare indium foils and equation 6.

Table 4.10

Thermal neutron fluence and total photoneutron yield assessed with the activation of bare foils.

LINAC energy	ϕ_{th} (cm ⁻²)	Q (Gy ⁻¹)
10 MV	7.72E+04	1.22E+11
15 MV	1.14E+06	2.06E+12
18 MV	2.18E+06	4.41E+12
20 MV	2.80E+06	5.33E+12

4.4 DISCUSSION

The total neutron fluence in table 4.2 exhibited a continual increase with accelerator energy, and, a dependence on the measurement position relative to the x-ray target. Neutron fluence values peak at the locations with the least amount of treatment head shielding, in this case at the sides of the accelerator head in the target plane. As seen in Table 4.2, the total neutron fluence is comparable at the symmetric positions. Two deviations from this trend are the number 6 and number 7 positions, which were higher than their counterparts, positions 10 and 11, respectively, by as much as 32 percent. This increase can be explained by the fact that those two positions were measured at about 5 cm from the accelerator frame for position 7 and 60 cm for position 6. The added fluence may be due to the scattering of the neutrons by the metallic parts in the accelerator. The dose equivalent data in Table 4.4 indicates the same trends as the neutron fluence data. Table 4.5 presents the quality factors obtained using data from the fluence moderator and the A-B type remmeter. The quality factors values in this table range between 8 and 10.

Data for the average energy in Table 4.6 indicate that the neutron average energy in the patient plane locations, are generally higher than the positions in the target plane and the above-target position. The highest measured average energy for the 10 MV accelerator (0.67 MeV) was in the patient plane, position 9. For the 15 MV accelerator, the highest average energy (0.83) was measured at positions 4 and 11, in the patient plane as well. Measured average neutron energies for the 18 MV and the 20 MV LINACs, show a somewhat uniform average energy in the patient plane, and the values vary very little from one position to another. Table 4.7 presents the neutron average direct energy calculated using McCall's cook-book method of NCRP-79. As can be seen from Table 4.7, the cook-book values for direct average energy are higher than the measured values by as much as 20 percent. It should be noted that the measured data included scatter, while the calculated values using the cook-book method did not. The calculated scattered neutrons average energies for the 13 measured positions, using the cook-book method, are presented as Table 4.8.

Table 4.9 is a summary of the calculated average energy using the Half-Energy-Layer method. Values from this table are typically between 10-50 percent lower than the measured values, with exceptions noted at a few positions for the 18 and 20 MV LINACs. The HEL average energies depend on the primary average energy in addition to the HEL values calculated in NCRP79, where several assumptions had to be made regarding spectra shape and treatment head shielding geometry design. On the other hand, the measured data depends on the assumptions made regarding the response of the remmeter and the fluence moderator to the neutron energy. Additionally, the remmeter and the fluence moderator were calibrated using a ^{252}Cf neutron source, which

has a different spectrum and higher average energy than that expected for a medical LINAC. It is difficult to ascertain which method has the larger error, hence, the lower reliability. However, since all the techniques gave values which are within a factor of 2 of each other, the cook-book method provides an adequate estimate of the average neutron energy of a LINAC spectra if measurements are prohibitive. If more detailed information is known, regarding the treatment head shielding, the HEL method is yet another method to obtain quick and adequate estimate of the average energy of the neutron spectra.

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CHAPTER V

SUMMARY AND CONCLUSIONS

This chapter presents a comparison of the neutron measurement results from the three measurement methods employed in this study. While there is no absolute standard with which to compare the measured results, there are acceptable operational standards based on available information, that can be compared. In addition, an inter-method comparison often leads to the choice of an appropriate method. Tables 5.1 through 5.4 are a comparative summary for 10, 15, 18, and 20 MV LINACs, respectively. Method 1.a in the table refers to the BDS spectral stripping method with the $1/E$ fluence shape assumption within each energy bin; method 1.b refers to the BDS spectral stripping method with the constant fluence shape within each energy bin; and, method 1.c refers to the BDS-BUNKI method. Method 2 refers to using the BUNKI code with the BSS data. Method 3 is the data from the fluence moderator/A-B remmeter combination.

5.1 FLUENCE COMPARISON

One obvious feature seen from these tables is that the total fluence calculated using the BDS method is the highest of all the methods. Further, the total neutron fluence from the BDS system, calculated using the stripping technique, is consistently higher than the BDS-BUNKI approach. For positions A, the neutron fluence values using BDS spectral stripping method (methods 1.a and 1.b), with both fluence assumptions within each energy bin, ranged from 1.39×10^6 [$\text{cm}^{-2} \text{ Gy}^{-1}$] and 3.90×10^7 [$\text{cm}^{-2} \text{ Gy}^{-1}$] and showed dependence on accelerator energy. Position B for all LINACs has the lowest fluence values, while position D has the highest.

Table 5.1

A summary comparison per position for all common calculated quantities for the 10 MV accelerator, all methods. Description of each method is discussed in text, chapter V page 95.

Position A	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 fix./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	1.39E+06	1.39E+06	8.07E+05	2.43E+05	2.16E+05
Avg. Energy	MeV	0.10	0.12	0.14	0.28	0.65
Dose Equiv.	Sv Gy ⁻¹	6.58E-05	7.77E-05	5.10E-05	2.26E-05	3.56E-05
h _φ	Sv cm ²	4.78E-11	5.60E-12	6.32E-11	9.3E-11	1.65E-10
Quality factor	N/A	N/A	N/A	6.8	7.9	9.2

Position B	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 fix./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	9.72E+05	9.72E+05	5.03E+05	1.63E+05 (1.67E+05)	1.32E+05
Avg. Energy	MeV	0.11	0.13	0.17	0.04 (0.10)	0.60
Dose Equiv.	Sv Gy ⁻¹	4.71E-05	5.50E-05	3.67E-05	4.83E-06 (9.05E-06)	2.05E-05
h _φ	Sv cm ²	4.85E-11	5.66E-11	7.30E-11	2.96E-11 (5.42E-11)	1.55E-10
Quality factor	N/A	N/A	N/A	7.3	4.5 (6.5)	9.1

Position C	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 fix./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	1.16E+06	1.16E+06	7.14E+05	2.10E+05	1.88E+05
Avg. Energy	MeV	0.11	0.13	0.16	0.19	0.51
Dose Equiv.	Sv Gy ⁻¹	5.94E-05	6.90E-05	4.79E-05	1.55E-05	2.61E-05
h _φ	Sv cm ²	5.12E-11	5.95E-11	6.71E-11	7.38E-11	1.39E-10
Quality factor	N/A	N/A	N/A	7.0	7.3	8.7

Position D	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 fix./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	1.21E+06	1.21E+06	7.30E+05	N/A	2.17E+05
Avg. Energy	MeV	0.11	0.13	0.16	N/A	0.43
Dose Equiv.	Sv Gy ⁻¹	6.10E-05	7.10E-05	4.84E-05	N/A	2.67E-05
h _φ	Sv cm ²	5.04E-11	5.87E-11	6.63E-11	N/A	1.23E-11
Quality factor	N/A	N/A	N/A	7.0	N/A	8.4

Table 5.2

A summary comparison per position for all common calculated quantities for the 15 MV accelerator, all methods. Description of each method is discussed in text, chapter V page 95.

Position A	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	1.32E+07	1.32E+07	6.56E+06	5.34E+06	3.05E+06
Avg. Energy	MeV	0.15	0.18	0.26	0.19	0.81
Dose Equiv.	Sv Gy ⁻¹	7.71E-04	8.87E-04	6.17E-04	4.14E-04	5.94E-04
h _φ	Sv cm ²	5.84E-11	6.72E-11	9.41E-11	7.75E-11	1.95E-10
Quality factors	N/A	N/A	N/A	8.0	7.5	9.7

Position B	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	9.04E+06	9.04E+06	4.67E+06	3.02E+06	2.08E+06
Avg. Energy	MeV	0.18	0.21	0.29	0.37	0.83
Dose Equiv.	Sv Gy ⁻¹	5.94E-04	6.66E-04	4.77E-04	2.68E-04	4.13E-04
h _φ	Sv cm ²	6.57E-11	7.37E-11	1.02E-10	8.87E-11	1.99E-10
Quality factor	N/A	N/A	N/A	8.2	7.4	9.8

Position C	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	1.07E+07	1.07E+07	6.07E+06	4.08E+06	2.48E+06
Avg. Energy	MeV	0.18	0.20	0.26	0.27	0.72
Dose Equiv.	Sv Gy ⁻¹	7.34E-04	8.19E-04	5.97E-04	3.58E-04	4.40E-04
h _φ	Sv cm ²	6.86E-11	7.65E-11	9.84E-11	8.77E-11	1.77E-10
Quality factors	N/A	N/A	N/A	8.2	7.6	9.5

Position D	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	1.57E+07	1.57E+07	8.46E+06	4.97E+06	3.16E+06
Avg. Energy	MeV	0.15	0.17	0.24	0.25	0.62
Dose Equiv.	Sv Gy ⁻¹	9.47E-04	1.08E-03	7.63E-04	4.32E-04	5.07E-04
h _φ	Sv cm ²	6.03E-11	6.88E-11	9.02E-11	8.69E-11	1.60E-10
Quality factor	N/A	N/A	N/A	7.9	7.7	9.1

Table 5.3

A summary comparison per position for all common calculated quantities for the 18 MV accelerator, all methods. Description of each method is discussed in text, chapter V page 95.

Position A	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	3.90E+07	3.90E+07	2.05E+07	7.72E+06	7.41E+06
Avg. Energy	MeV	0.15	0.17	0.23	0.42	0.86
Dose Equiv.	Sv Gy ⁻¹	2.20E-03	2.53E-03	1.74E-03	8.83E-04	1.50E-03
h_ϕ	Sv cm ²	5.64E-11	6.49E-11	8.49E-11	1.14E-10	2.02E-10
Quality factor	N/A	N/A	N/A	7.7	8.3	9.9

Position B	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	2.94E+07	2.94E+07	1.51E+07	5.61E+06	4.77E+06
Avg. Energy	MeV	0.16	0.18	0.25	0.45	0.79
Dose Equiv.	Sv Gy ⁻¹	1.66E-03	1.91E-03	1.32E-03	5.60E-04	9.10E-04
h_ϕ	Sv cm ²	5.65E-11	6.60E-11	8.74E-11	9.98E-11	1.91E-10
Quality factor	N/A	N/A	N/A	7.7	7.7	9.1

Position C	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	3.10E+07	3.10E+07	2.11E+07	6.34E+06	5.75E+06
Avg. Energy	MeV	0.14	0.16	0.22	0.30	0.66
Dose Equiv.	Sv Gy ⁻¹	2.21E-03	2.55E-03	1.76E-03	7.12E-04	9.68E-04
h_ϕ	Sv cm ²	7.13E-11	8.23E-11	8.34E-11	1.12E-10	1.68E-10
Quality factor	N/A	N/A	N/A	7.7	8.6	9.3

Position D	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	4.57E+07	4.57E+07	2.28E+07	N/A	7.09E+06
Avg. Energy	MeV	0.14	0.16	0.24	N/A	0.67
Dose Equiv.	Sv Gy ⁻¹	2.58E-03	2.96E-03	2.06E-03	N/A	1.21E-03
h_ϕ	Sv cm ²	5.65E-11	6.48E-11	9.04E-11	N/A	1.71E-10
Quality factor	N/A	N/A	N/A	7.9	N/A	9.3

Table 5.4

A summary comparison per position for all common calculated quantities for the 20 MV accelerator, all methods. Description of each method is discussed in text, chapter V page 95.

Position A	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	3.81E+07	3.81E+07	1.90E+07	1.14E+07	7.83E+06
Avg. Energy	MeV	0.18	0.20	0.29	0.29	0.81
Dose Equiv.	Sv Gy ⁻¹	2.34E-03	2.65E-03	1.86E-03	1.19E-03	1.52E-03
h _φ	Sv cm ²	6.14E-11	9.96E-11	9.79E-11	1.04E-10	1.94E-10
Quality factor	N/A	N/A	N/A	8.1	8.4	9.7

Position B	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	2.86E+07	2.86E+07	1.17E+07	7.54E+06	5.05E+06
Avg. Energy	MeV	0.21	0.24	0.41	0.19	0.80
Dose Equiv.	Sv Gy ⁻¹	1.14E-03	1.36E-03	1.55E-03	6.05E-04	9.77E-04
h _φ	Sv cm ²	3.99E-11	4.76E-11	1.32E-10	8.02E-11	1.93E-10
Quality factor	N/A	N/A	N/A	8.9	7.7	9.7

Position C	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	3.93E+07	3.93E+07	2.11E+07	9.98E+06	7.65E+06
Avg. Energy	MeV	0.10	0.12	0.27	0.35	0.61
Dose Equiv.	Sv Gy ⁻¹	1.51E-03	1.84E-03	2.04E-03	1.12E-03	1.25E-03
h _φ	Sv cm ²	3.84E-11	4.68E-11	9.67E-11	1.12E-10	1.63E-10
Quality factor	N/A	N/A	N/A	8.1	8.5	9.2

Position D	Units	Method 1a [1/E]	Method 1b [Constant Fluence]	Method 1c [BUNKI]	Method 2 [BUNKI]	Method 3 flx./remmeter
Total Fluence	cm ⁻² Gy ⁻¹	4.53E+07	4.53E+07	1.75E+07	N/A	8.67E+06
Avg. Energy	MeV	0.19	0.21	0.40	N/A	0.66
Dose Equiv.	Sv Gy ⁻¹	3.04E-03	3.41E-03	2.34E-03	N/A	1.45E-03
h _φ	Sv cm ²	6.71E-03	7.53E-11	1.31E-10	N/A	1.67E-10
Quality factors	N/A	N/A	N/A	9.0	N/A	9.3

The neutron fluence values from the BDS-BUNKI method (1.c), are generally lower than values from the BDS spectral stripping methods (1.a and 1.b). However, the values indicate dependence on accelerator energy and measurement positions. Exceptions are noted for the 20 MV LINAC for which the values are similar or less than those for the 18 MV. Neutron fluence values measured using the BSS and the indium foil activation methods, exhibited the closest agreement, in regard to the dependence of the measurements on accelerator energy and measurement positions.

The neutron fluence per unit photon dose plotted versus accelerator energy for the BSS method is presented in Figure 5.1. Similar plots of the neutron fluence for the other two methods, as a function of LINAC energy, are presented in Appendix E. An important feature of these plots is that the measured values using the fluence moderator and the BDS methods are unexpectedly high for the 18 MV LINAC, relative to that exhibited by the BSS results.

An explanation for the higher response of the fluence moderator and the BDS methods to the 18 MV LINAC, may be the nature of the energy response of the two detector systems. Additionally, it takes 30 percent more electrons incident on the target for the 18 MV LINAC, relative to the 20 MV LINAC, to produce one unit of dose at isocenter. From the photoneutron cross section information, it is expected that the 20 MV LINAC will produce approximately 20 percent more neutrons than the 18 MV LINAC per incident electron. Hence, the 18 MV will have about 10 percent net increase in neutron production per unit dose delivered over the 20 MV LINAC. This behavior by the fluence moderator and the BDS system is not exhibited by the BSS method.

Figure 5.1. Neutron fluence [$\text{cm}^{-2} \text{Gy}^{-1}$] as a function of accelerator energy using the BSS method.

5.2 DOSE EQUIVALENT COMPARISON

The dose equivalent values obtained using the BSS method are presented as a plot of dose equivalent [Sv Gy^{-1}] versus accelerator energy in Figure 5.2. Examination of this plot, indicates an increase in dose equivalent with accelerator energy. The dose equivalent values for the four energy LINACs exhibited the same positional dependence, position A with the highest values, and position B with the lowest values. The one exception observed from the plot, is the position B value for the 20 MV LINAC.

The dose equivalent values ranged from a minimum value of 4.83×10^{-6} [Sv Gy^{-1}] for position B for the 10 MV LINAC to a maximum value of 1.19×10^{-3} [Sv Gy^{-1}] for position A for the 20 MV LINAC. Similar plots for the dose equivalent versus accelerator energy using the other methods are presented in Appendix E (Figures E.2 and E.4). Many of the same observations seen with the neutron fluence plots can be made regarding the dose equivalent plots. The BSS and the fluence moderator/remmeter methods seem to agree rather well, with the BDS values being consistently higher. Similar plots of the neutron fluence and the dose equivalent versus accelerator energy, were made for positions A, B, and C (Figures E.5 through E.10). The plot for position D has no data for the BSS method since it was not measured for all the LINACs at this position.

5.3 AVERAGE ENERGY COMPARISON

The average energy results using the BDS spectral stripping method averaged about 0.1 MeV for the 10 MV LINAC, and about 0.2 MeV for the LINACs of 15, 18, and 20 MV (Tables 5.1 through 5.4). The BDS-BUNKI average energies exhibited some variations with accelerator energy, but not versus

Figure 5.2. Neutron dose equivalent [Sv Gy⁻¹] as a function of accelerator energy using the BSS method.

measurement positions. The values from the BDS-BUNKI averaged about 0.2 MeV for the 10 MV LINAC, and about 0.3 MeV for the 15 MV, 18 MV, and 20 MV LINACs, respectively. The BSS method gave the highest average energies for the 18 MV LINAC, about 0.4 MeV. For the other LINACs the values ranged between 0.2 and 0.4 MeV. The average energy for the 10 MV at position B (0.04 MeV) is very low and not consistent with other values. It is believed that there was an experimental error or an error in reading the TLD for 12 inch sphere for that position. Several attempts were made to see the effect of removing the 12 inch sphere data will have on the results. The BUNKI unfolding code had a fitting error of about 20 percent in trying to unfold the data without the 12 inch sphere data. Results of these attempts are provided in parenthesis in Table 5.1 under the original values for comparison.

The average energy from the fluence moderator/remmeter combination gave the highest values of the three methods. These values ranged from a low of 0.4 MeV for the 10 MV LINAC at position D, and a high of 0.8 MeV at several measurement positions. This method gave a more uniform distribution of average energy than the other methods. Values of average energy, obtained using the half-energy-layer (HEL) method, are higher than the average energy values from the BDS and BSS methods. The HEL average energy values are very comparable to measured values by the fluence moderator/remmeter combination. However, the HEL method of calculating average energy does not consider the room scatter contribution, where other experimental methods do. Average energies calculated using the HEL method are obtained by finding the thickness of the material that reduces the initial neutron energy by one-half. This, however, does not take into account the effect that the material has on the

neutrons' spectral energy distribution after they have penetrated the material, nor does it consider the detection system response to the neutron distribution. In addition, HEL data were extrapolated to the low energy region, due to the lack of actual data below 0.68 MeV. It is not clear how good is this approximation, since neutrons behave differently as their energy drops, and this will impact the calculations.

5.4 NEUTRON SPECTRA

The measured neutron spectra looked reasonable for the most part. However, the double peak in the spectra obtained using the BDS-BUNKI method cannot be explained. Many attempts were made to see if this is the result of some initial solution biasing, by manipulating the input parameters of the BUNKI code such as smoothing, number of iterations, and initial solution assumptions. No biasing was found. The spectra from the BDS-BUNKI for the four LINACs at all measurement positions exhibited the double peak feature.

Possible explanations of the BDS-BUNKI output could be attributed directly to the BDS response matrix. This matrix was extracted from response curves provided by the manufacturer. These curves are very broad and some points on the curves are extrapolations. Hence, the extraction of the data to build the response matrix was subjective, and it is very difficult to estimate the effect on the total response of the BDS system. Another possible reason could be related to the way BUNKI uses the input data. The BUNKI code has energy bin resolution that is better than that of the stripping technique by a factor of 5. Hence, the method becomes highly sensitive to oscillations in the number of bubbles detected in each energy bin, especially in the higher energy bins where it

is not expected to have many neutrons present. Also, as reported in the radiosopic portion of this study, some oscillations were observed in the sensitivity check of the BDS system against the radioisotopic neutron source for the duration of the study.

The measured spectra obtained from the BDS data using spectral stripping unfolding techniques gave similar results for every LINAC and all positions. The BDS spectrometer is still in the development stage and very environment-sensitive. Thus, if any environmental conditions do interfere, it is not possible to attempt corrections with any degree of certainty. The same thing was observed from the BDS spectral results with the BUNKI code.

The spectra measured using the BSS data obtained by the BUNKI code seems to be internally consistent. This method, too, had some approximations. The response function used in the unfolding code was devised initially for use by a LiI(Eu) detector, and not for TLDs. It is believed that both will exhibit similar behavior, except for the magnitude of the response. It is a reasonably safe assumption that they will have similar response function, since detection of neutrons in both systems is via the interaction of thermal neutrons with ^6Li . The sizes of the two detectors are different, but it is doubtful that this will have an effect on the shape of the resulting response. One major drawback is that it is not practical to apply the bare and cadmium covered TLD information to the unfolding code due to their significantly different responses. This reduced the number of detectors to be used in the unfolding by two. Of course, the more detectors used, the better the estimate of the spectra.

The BSS spectra obtained as a function of measurement position for each of the accelerators are presented as Figures 5.3 through 5.6. These graphs show

positional dependence as evident by the peak energy or the shape of the measured spectra. The only exception is the 20 MV accelerator, where the spectral shapes are similar, and only the magnitude reflects the distance from the target.

Another way the above spectral information can be viewed is as a function of accelerator energy for each position. These spectra are illustrated in Figures 5.7 through 5.9. These figures show the consistency of the method in measuring the neutron spectra at the same location, and the effect of the increase of the accelerator energy is reflected in the magnitude. Similar analysis was made for the spectra produced by the BUNKI code for the BDS system and is provided as Appendix D. It is worth mentioning that the reliability of the BDS method is in question for several reasons. The number and type of detectors in the spectrometer, six threshold detectors in this case, is not enough to adequately characterize the neutron spectrum with a good energy resolution. The statistical fluctuations in each energy bin, with respect to the number of bubbles, causes a large uncertainty in the resulting spectra. This is more serious, however, in the case of spectral stripping technique where the largest statistical errors are propagated back from the highest energy bins of the spectrometer to the lowest. Additionally, the detector response matrix is not well characterized, and more research regarding its behavior with different neutron field is needed. Hence, the BDS data collected here may best be used as a benchmark for future work.

No spectral information can be obtained by using the fluence moderator/A-B remmeter combination. The method however, is widely used in medical electron accelerator facilities around the world because of their simplicity.

Figure 5.3. Neutron spectra for the 10 MV accelerator, measured using the BSS method for the three locations. Digital data are presented in tables in appendix B.

Figure 5.4. Neutron spectra for the 15 MV accelerator, measured using the BSS method for the three locations. Digital data are presented in tables in appendix B.

Figure 5.5. Neutron spectra for the 18 MV accelerator, measured using the BSS method for the three locations. Digital data are presented in tables in appendix B.

Figure 5.6. Neutron spectra for the 20 MV accelerator, measured using the BSS method for the three locations. Digital data are presented in tables in appendix B.

Figure 5.7. Neutron spectra for position A, measured using the BSS method for the four accelerator energies. Digital data are presented in tables in appendix B.

Figure 5.8. Neutron spectra for position B, measured using the BSS method for the four accelerator energies. Digital data are presented in tables in appendix B.

Figure 5.9. Neutron spectra for position C, measured using the BSS method for the four accelerator energies. Digital data are presented in tables in appendix B.

As a whole, the BDS results showed higher total fluence, lower average energy, and lower dose equivalent than the other methods. The fluence moderator/A-B remmeter combination gave the lowest total fluence, and the highest average energy of the three measurement methods. The average energy values obtained using the Half-Energy-Layer method discussed in section 4.3.5 and summarized in table 4.8, are closer to the fluence moderator/remmeter combination results than to any of the other methods. The fluence-to-dose-equivalent conversion factors obtained from the various methods ranged between 2.0×10^{-10} [Sv cm²] and 5.6×10^{-12} [Sv cm²]. The fluence moderator/remmeter h_ϕ values are the highest among all methods.

One of the disadvantages of the fluence moderator/remmeter method is its dependence on the detectors' response to neutron energies. Also, the detectors are usually calibrated with a radioisotopic source. In this work, a ²⁵²Cf neutron source was used. It is expected that this will effect the response somewhat, since the average energy of the ²⁵²Cf neutron source is around 2 MeV, and the average energy penetrating the head shielding is expected to be about 0.5 MeV. This effect cannot be quantified adequately unless the detectors are calibrated with fields similar to those produced by medical LINACs, or corrections are made based on accepted neutron spectral distributions.

While none of the measurement and calculational methods exhibit enough agreement to categorically advocate the dominance of any particular method, the author believes that the Bonner Sphere Spectrometer system offers the best energy resolution and most well understood response function characteristics. This makes it the detector system of choice with regard to spectral capabilities. In the absence of time, resources, expertise, and availability of a Bonner Sphere

Spectrometer system, the fluence moderator and remmeter combination yield close and in most cases conservative values for neutrons, with respect to Bonner Sphere assessed results.

Calculational methods produce average energy information in close agreement with that obtained using the fluence moderator and remmeter combination, and may be just as accurate. Because of the variables and uncertainties associated with both measurement and calculational systems, it is difficult to define "the best" approach for assessment of any particular neutron dosimetric quantity. Rather, the author feels that one of the principle contribution of this work is to outline the uncertainties and variabilities, and to define the need for improvement in accepted methods. The author believes that the greatest short term advances may come with a rigorous computational approach (i.e. Monte Carlo), with detailed modeling of accelerator structure, geometry, shielding, and room scattering effects.

APPENDIX A

Bubble Detector Spectrometer Results Using BUNKI

Appendix A contains the BUNKI code outputs of the calculated spectra using the Bubble detector Spectrometer (BDS) data as inputs to BUNKI. Spectra for all four accelerators and all measured positions are included. The first column of the table is the bin number from 1 to 31. The second column is the energy bin structure used by BUNKI. The third and fourth columns are the fluence (cm^{-2}) and the fluence per unit lethargy ($\text{cm}^{-2}/\text{LETH}$) per bin respectively. The fifth column is the calculated dose (RAD) per energy bin, and the last column is the calculated dose equivalent (REM) per energy bin. The units in these tables are the same units that BUNKI outputs. All BUNKI outputs are normalized to 1 photon RAD delivered by each accelerator at isocenter.

Table A.1

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 10 MV accelerator energy at position A.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	2.57E+03	7.89E+03	1.45E-06	3.89E-06
17	5.25E-02	2.61E+03	8.00E+03	1.73E-06	7.00E-06
18	1.11E-01	1.38E+03	4.22E+03	1.08E-06	6.57E-06
19	2.24E-01	2.17E+02	7.13E+02	2.25E-07	1.80E-06
20	4.51E-01	5.11E+00	1.68E+01	7.43E-09	7.24E-08
21	9.07E-01	1.26E+03	4.13E+03	2.82E-06	3.00E-05
22	1.87E+00	3.28E+01	1.04E+02	1.12E-07	1.15E-06
23	3.68E+00	1.03E+01	3.50E+01	4.33E-08	4.10E-07
24	7.41E+00	6.00E-01	1.97E+00	3.47E-09	2.44E-08
25	1.49E+01	3.79E-02	1.25E-01	2.51E-10	1.56E-09
26	2.58E+01	6.72E-04	2.82E-03	6.11E-12	2.93E-11
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.2

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 10 MV accelerator energy at position B.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	1.37E+03	4.21E+03	7.71E-07	2.08E-06
17	5.25E-02	1.39E+03	4.27E+03	9.22E-07	3.73E-06
18	1.11E-01	9.68E+02	2.97E+03	7.60E-07	4.62E-06
19	2.24E-01	3.21E+02	1.06E+03	3.34E-07	2.67E-06
20	4.51E-01	3.29E+01	1.08E+02	4.79E-08	4.66E-07
21	9.07E-01	9.18E+02	3.02E+03	2.06E-06	2.19E-05
22	1.87E+00	2.31E+01	7.35E+01	7.88E-08	8.11E-07
23	3.68E+00	8.00E+00	2.73E+01	3.38E-08	3.20E-07
24	7.41E+00	7.26E-01	2.39E+00	4.19E-09	2.95E-08
25	1.49E+01	4.61E-02	1.52E-01	3.05E-10	1.89E-09
26	2.58E+01	6.72E-04	2.80E-03	6.00E-12	2.90E-11
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.3

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 10 MV accelerator energy at position C.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	2.31E+03	7.10E+03	1.30E-06	3.50E-06
17	5.25E-02	2.35E+03	7.20E+03	1.56E-06	6.30E-06
18	1.11E-01	1.07E+03	3.28E+03	8.39E-07	5.10E-06
19	2.24E-01	1.07E+02	3.51E+02	1.11E-07	8.85E-07
20	4.51E-01	7.62E-01	2.50E+00	1.11E-09	1.08E-08
21	9.07E-01	1.25E+03	4.13E+03	2.82E-06	3.00E-05
22	1.87E+00	4.01E+01	1.28E+02	1.37E-07	1.41E-06
23	3.68E+00	1.05E+01	3.57E+01	4.42E-08	4.19E-07
24	7.41E+00	6.18E-01	2.03E+00	3.57E-09	2.52E-08
25	1.49E+01	3.90E-02	1.28E-01	2.59E-10	1.61E-09
26	2.58E+01	7.10E-04	2.98E-03	6.46E-12	3.09E-11
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.4

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 10 MV accelerator energy at position D.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	2.32E+03	7.11E+03	1.30E-06	3.51E-06
17	5.25E-02	2.35E+03	7.21E+03	1.56E-06	6.31E-06
18	1.11E-01	1.18E+03	3.63E+03	9.27E-07	5.64E-06
19	2.24E-01	1.58E+02	5.21E+02	1.64E-07	1.31E-06
20	4.51E-01	2.31E+00	7.58E+00	3.35E-09	3.27E-08
21	9.07E-01	1.23E+03	4.05E+03	2.76E-06	2.94E-05
22	1.87E+00	4.90E+01	1.56E+02	1.67E-07	1.72E-06
23	3.68E+00	1.27E+01	4.33E+01	5.36E-08	5.07E-07
24	7.41E+00	7.57E-01	2.49E+00	4.37E-09	3.08E-08
25	1.49E+01	4.78E-02	1.57E-01	3.16E-10	1.96E-09
26	2.58E+01	6.72E-04	2.82E-03	6.11E-12	2.93E-11
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.5

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 15 MV accelerator energy at position A.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	1.54E+04	4.73E+04	8.67E-06	2.33E-05
17	5.25E-02	1.56E+04	4.80E+04	1.04E-05	4.20E-05
18	1.11E-01	1.19E+04	3.64E+04	9.30E-06	5.66E-05
19	2.24E-01	4.84E+03	1.59E+04	5.02E-06	4.01E-05
20	4.51E-01	6.41E+02	2.11E+03	9.32E-07	9.08E-06
21	9.07E-01	1.44E+04	4.73E+04	3.22E-05	3.43E-04
22	1.87E+00	2.20E+03	7.01E+03	7.51E-06	7.73E-05
23	3.68E+00	4.60E+02	1.57E+03	1.94E-06	1.84E-05
24	7.41E+00	1.74E+02	5.72E+02	1.01E-06	7.08E-06
25	1.49E+01	5.72E+00	1.88E+01	3.79E-08	2.35E-07
26	2.58E+01	4.11E-02	1.73E-01	3.74E-10	1.79E-09
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.6

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 15 MV accelerator energy at position B.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	1.14E+04	3.49E+04	6.39E-06	1.72E-05
17	5.25E-02	1.15E+04	3.54E+04	7.64E-06	3.09E-05
18	1.11E-01	7.55E+03	2.32E+04	5.92E-06	3.60E-05
19	2.24E-01	1.96E+03	6.44E+03	2.03E-06	1.62E-05
20	4.51E-01	7.51E+01	2.47E+02	1.09E-07	1.06E-06
21	9.07E-01	1.15E+04	3.78E+04	2.57E-05	2.74E-04
22	1.87E+00	2.39E+03	7.59E+03	8.13E-06	8.37E-05
23	3.68E+00	2.98E+02	1.02E+03	1.26E-06	1.19E-05
24	7.41E+00	1.48E+02	4.85E+02	8.52E-07	6.01E-06
25	1.49E+01	4.23E+00	1.39E+01	2.80E-08	1.74E-07
26	2.58E+01	3.02E-02	1.27E-01	2.74E-10	1.31E-09
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.7

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 15 MV accelerator energy at position C.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	1.60E+04	4.92E+04	9.02E-06	2.43E-05
17	5.25E-02	1.63E+04	4.99E+04	1.08E-05	4.37E-05
18	1.11E-01	8.44E+03	2.59E+04	6.62E-06	4.03E-05
19	2.24E-01	1.08E+03	3.56E+03	1.12E-06	8.98E-06
20	4.51E-01	6.67E+00	2.19E+01	9.69E-09	9.44E-08
21	9.07E-01	1.66E+04	5.47E+04	3.73E-05	3.97E-04
22	1.87E+00	2.01E+03	6.37E+03	6.83E-06	7.03E-05
23	3.68E+00	2.10E+02	7.16E+02	8.87E-07	8.40E-06
24	7.41E+00	8.90E+01	2.93E+02	5.14E-07	3.62E-06
25	1.49E+01	3.17E+00	1.04E+01	2.10E-08	1.30E-07
26	2.58E+01	2.29E-02	9.63E-02	2.08E-10	9.98E-10
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.8

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 15 MV accelerator energy at position D.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	2.26E+04	6.95E+04	1.27E-05	3.43E-05
17	5.25E-02	2.30E+04	7.05E+04	1.52E-05	6.17E-05
18	1.11E-01	1.36E+04	4.18E+04	1.07E-05	6.50E-05
19	2.24E-01	2.67E+03	8.78E+03	2.77E-06	2.22E-05
20	4.51E-01	5.79E+01	1.90E+02	8.43E-08	8.21E-07
21	9.07E-01	1.95E+04	6.42E+04	4.37E-05	4.66E-04
22	1.87E+00	2.66E+03	8.44E+03	9.04E-06	9.31E-05
23	3.68E+00	3.76E+02	1.28E+03	1.59E-06	1.50E-05
24	7.41E+00	1.15E+02	3.78E+02	6.64E-07	4.68E-06
25	1.49E+01	1.16E+00	3.81E+00	7.66E-09	4.76E-08
26	2.58E+01	7.84E-03	3.29E-02	7.13E-11	3.42E-10
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.9

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 18 MV accelerator energy at position A.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	5.44E+04	1.67E+05	3.06E-05	8.23E-05
17	5.25E-02	5.51E+04	1.69E+05	3.66E-05	1.48E-04
18	1.11E-01	3.64E+04	1.12E+05	2.86E-05	1.74E-04
19	2.24E-01	1.01E+04	3.31E+04	1.05E-05	8.36E-05
20	4.51E-01	5.71E+02	1.88E+03	8.30E-07	8.08E-06
21	9.07E-01	4.03E+04	1.33E+05	9.05E-05	9.64E-04
22	1.87E+00	6.19E+03	1.97E+04	2.11E-05	2.17E-04
23	3.68E+00	1.00E+03	3.42E+03	4.23E-06	4.01E-05
24	7.41E+00	5.90E+02	1.94E+03	3.41E-06	2.40E-05
25	1.49E+01	1.90E+01	6.24E+01	1.26E-07	7.80E-07
26	2.58E+01	1.36E-01	5.73E-01	1.24E-09	5.94E-09
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.10

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 18 MV accelerator energy at position B.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	3.92E+04	1.20E+05	2.20E-05	5.93E-05
17	5.25E-02	3.97E+04	1.22E+05	2.64E-05	1.07E-04
18	1.11E-01	2.76E+04	8.46E+04	2.16E-05	1.32E-04
19	2.24E-01	8.78E+03	2.89E+04	9.11E-06	7.28E-05
20	4.51E-01	6.97E+02	2.29E+03	1.01E-06	9.87E-06
21	9.07E-01	2.75E+04	9.05E+04	6.17E-05	6.57E-04
22	1.87E+00	6.19E+03	1.97E+04	2.11E-05	2.17E-04
23	3.68E+00	1.06E+03	3.62E+03	4.48E-06	4.24E-05
24	7.41E+00	4.75E+02	1.56E+03	2.75E-06	1.93E-05
25	1.49E+01	2.69E+01	8.84E+01	1.78E-07	1.11E-06
26	2.58E+01	2.06E-01	8.66E-01	1.88E-09	8.98E-09
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.11

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 18 MV accelerator energy at position C.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	5.63E+04	1.73E+05	3.17E-05	8.53E-05
17	5.25E-02	5.71E+04	1.75E+05	3.79E-05	1.54E-04
18	1.11E-01	3.74E+04	1.15E+05	2.94E-05	1.79E-04
19	2.24E-01	1.01E+04	3.32E+04	1.05E-05	8.38E-05
20	4.51E-01	5.44E+02	1.79E+03	7.90E-07	7.70E-06
21	9.07E-01	4.39E+04	1.45E+05	9.85E-05	1.05E-03
22	1.87E+00	4.31E+03	1.37E+04	1.47E-05	1.51E-04
23	3.68E+00	8.23E+02	2.81E+03	3.47E-06	3.29E-05
24	7.41E+00	3.41E+02	1.12E+03	1.97E-06	1.39E-05
25	1.49E+01	1.82E+01	6.00E+01	1.21E-07	7.50E-07
26	2.58E+01	1.38E-01	5.81E-01	1.26E-09	6.02E-09
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.12

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 18 MV accelerator energy at position D.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	5.69E+04	1.75E+05	3.20E-05	8.61E-05
17	5.25E-02	5.77E+04	1.77E+05	3.83E-05	1.55E-04
18	1.11E-01	4.02E+04	1.24E+05	3.16E-05	1.92E-04
19	2.24E-01	1.28E+04	4.23E+04	1.33E-05	1.07E-04
20	4.51E-01	9.50E+02	3.12E+03	1.38E-06	1.35E-05
21	9.07E-01	5.15E+04	1.70E+05	1.16E-04	1.23E-03
22	1.87E+00	6.00E+03	1.91E+04	2.05E-05	2.11E-04
23	3.68E+00	1.16E+03	3.94E+03	4.88E-06	4.62E-05
24	7.41E+00	4.46E+02	1.47E+03	2.58E-06	1.82E-05
25	1.49E+01	7.06E+00	2.32E+01	4.68E-08	2.90E-07
26	2.58E+01	4.86E-02	2.04E-01	4.42E-10	2.12E-09
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.13

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 20 MV accelerator energy at position A.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	4.73E+04	1.45E+05	2.66E-05	7.16E-05
17	5.25E-02	4.79E+04	1.47E+05	3.18E-05	1.29E-04
18	1.11E-01	3.22E+04	9.89E+04	2.53E-05	1.54E-04
19	2.24E-01	9.10E+03	2.99E+04	9.44E-06	7.55E-05
20	4.51E-01	4.66E+02	1.53E+03	6.78E-07	6.60E-06
21	9.07E-01	4.07E+04	1.34E+05	9.12E-05	9.72E-04
22	1.87E+00	1.04E+04	3.31E+04	3.55E-05	3.65E-04
23	3.68E+00	1.33E+03	4.53E+03	5.61E-06	5.31E-05
24	7.41E+00	6.66E+02	2.19E+03	3.85E-06	2.71E-05
25	1.49E+01	1.62E+02	5.33E+02	1.07E-06	6.66E-06
26	2.58E+01	1.99E+00	8.35E+00	1.81E-08	8.66E-08
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.14

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 20 MV accelerator energy at position B.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	2.23E+04	6.86E+04	1.26E-05	3.38E-05
17	5.25E-02	2.26E+04	6.95E+04	1.50E-05	6.08E-05
18	1.11E-01	1.65E+04	5.06E+04	1.29E-05	7.88E-05
19	2.24E-01	5.68E+03	1.87E+04	5.90E-06	4.72E-05
20	4.51E-01	3.59E+02	1.18E+03	5.22E-07	5.09E-06
21	9.07E-01	3.80E+04	1.25E+05	8.52E-05	9.08E-04
22	1.87E+00	9.73E+03	3.09E+04	3.31E-05	3.41E-04
23	3.68E+00	1.07E+03	3.65E+03	4.52E-06	4.27E-05
24	7.41E+00	5.26E+02	1.73E+03	3.04E-06	2.14E-05
25	1.49E+01	1.83E+02	6.00E+02	1.21E-06	7.50E-06
26	2.58E+01	2.81E+00	1.18E+01	2.56E-08	1.23E-07
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.15

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 20 MV accelerator energy at position C.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	5.48E+04	1.68E+05	3.08E-05	8.29E-05
17	5.25E-02	5.55E+04	1.71E+05	3.69E-05	1.49E-04
18	1.11E-01	3.29E+04	1.01E+05	2.58E-05	1.57E-04
19	2.24E-01	6.32E+03	2.08E+04	6.56E-06	5.24E-05
20	4.51E-01	1.19E+02	3.89E+02	1.72E-07	1.68E-06
21	9.07E-01	5.08E+04	1.67E+05	1.14E-04	1.21E-03
22	1.87E+00	9.16E+03	2.91E+04	3.12E-05	3.21E-04
23	3.68E+00	9.46E+02	3.23E+03	3.99E-06	3.78E-05
24	7.41E+00	4.57E+02	1.50E+03	2.64E-06	1.86E-05
25	1.49E+01	1.57E+02	5.16E+02	1.04E-06	6.44E-06
26	2.58E+01	2.34E+00	9.82E+00	2.13E-08	1.02E-07
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table A.16

The BUNKI code output results of the Bubble Detector Spectrometer (BDS) data for the 20 MV accelerator energy at position D.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	6.83E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	1.45E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	3.06E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	6.48E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	1.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7	2.90E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	6.14E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	1.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	2.75E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	5.93E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	1.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13	2.61E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
14	5.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	1.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16	2.48E-02	3.18E+04	9.76E+04	1.79E-05	4.81E-05
17	5.25E-02	3.22E+04	9.90E+04	2.14E-05	8.66E-05
18	1.11E-01	2.43E+04	7.47E+04	1.91E-05	1.16E-04
19	2.24E-01	9.35E+03	3.08E+04	9.70E-06	7.76E-05
20	4.51E-01	7.79E+02	2.56E+03	1.13E-06	1.10E-05
21	9.07E-01	6.27E+04	2.07E+05	1.41E-04	1.50E-03
22	1.87E+00	1.16E+04	3.69E+04	3.96E-05	4.07E-04
23	3.68E+00	1.59E+03	5.40E+03	6.69E-06	6.33E-05
24	7.41E+00	5.20E+02	1.71E+03	3.00E-06	2.12E-05
25	1.49E+01	2.09E+02	6.88E+02	1.39E-06	8.60E-06
26	2.58E+01	3.43E+00	1.44E+01	3.12E-08	1.49E-07
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

APPENDIX B

Bonner Sphere Spectrometer Results Using BUNKI

Appendix A contains the BUNKI code output of the calculated spectra using the Bonner Sphere Spectrometer data as inputs to BUNKI. Spectra for all four accelerators and all measured positions are included. Discreption of the data of these tables is similar to that of Appendix A above, except that the TLD data containe less number of positions than that of the BDS spectra.

Table B.1

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 10 MV accelerator energy at position A.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	1.90E+00	1.17E+00	9.99E-10	2.19E-09
2	6.83E-07	4.20E+00	1.93E+01	2.56E-09	5.17E-09
3	1.45E-06	7.38E+00	2.26E+01	4.55E-09	9.25E-09
4	3.06E-06	8.90E+00	2.73E+01	5.46E-09	1.11E-08
5	6.48E-06	1.09E+01	3.35E+01	6.62E-09	1.34E-08
6	1.37E-05	1.36E+01	4.17E+01	8.16E-09	1.65E-08
7	2.90E-05	1.72E+01	5.27E+01	1.02E-08	2.05E-08
8	6.14E-05	2.19E+01	6.72E+01	1.30E-08	2.58E-08
9	1.30E-04	2.83E+01	8.69E+01	1.67E-08	3.29E-08
10	2.75E-04	3.68E+01	1.13E+02	2.10E-08	4.13E-08
11	5.93E-04	4.90E+01	1.47E+02	2.68E-08	5.29E-08
12	1.23E-03	6.12E+01	1.92E+02	3.21E-08	6.36E-08
13	2.61E-03	8.14E+01	2.50E+02	4.19E-08	8.31E-08
14	5.53E-03	1.06E+02	3.25E+02	5.37E-08	1.07E-07
15	1.17E-02	1.37E+02	4.21E+02	6.91E-08	1.38E-07
16	2.48E-02	1.78E+02	5.48E+02	1.00E-07	2.70E-07
17	5.25E-02	2.35E+02	7.21E+02	1.56E-07	6.31E-07
18	1.11E-01	3.13E+02	9.60E+02	2.45E-07	1.49E-06
19	2.24E-01	3.65E+02	1.20E+03	3.79E-07	3.03E-06
20	4.51E-01	3.56E+02	1.17E+03	5.18E-07	5.04E-06
21	9.07E-01	2.33E+02	7.67E+02	5.23E-07	5.57E-06
22	1.87E+00	1.05E+02	3.35E+02	3.59E-07	3.70E-06
23	3.68E+00	4.48E+01	1.53E+02	1.89E-07	1.79E-06
24	7.41E+00	1.14E+01	3.75E+01	6.59E-08	4.65E-07
25	1.49E+01	5.53E-01	1.82E+00	3.66E-09	2.27E-08
26	2.58E+01	4.05E-03	1.70E-02	3.68E-11	1.76E-10
27	4.47E+01	3.72E-05	1.56E-04	3.57E-13	1.65E-12
28	7.73E+01	3.47E-07	1.46E-06	3.51E-15	1.63E-14
29	1.34E+02	3.27E-09	1.37E-08	3.71E-17	1.64E-16
30	2.31E+02	3.10E-11	1.30E-10	4.61E-19	1.71E-18
31	4.00E+02	3.00E-13	1.26E-12	5.39E-21	1.91E-20

Table B.2

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 10 MV accelerator energy at position B.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	2.19E-06	1.36E-06	1.15E-15	2.52E-15
2	6.83E-07	7.39E-06	3.40E-05	4.50E-15	9.10E-15
3	1.45E-06	2.88E-05	8.83E-05	1.78E-14	3.61E-14
4	3.06E-06	8.54E-05	2.62E-04	5.24E-14	1.06E-13
5	6.48E-06	2.78E-04	8.52E-04	1.69E-13	3.41E-13
6	1.37E-05	9.87E-04	3.03E-03	5.93E-13	1.20E-12
7	2.90E-05	3.77E-03	1.16E-02	2.25E-12	4.50E-12
8	6.14E-05	1.51E-02	4.63E-02	8.95E-12	1.78E-11
9	1.30E-04	6.35E-02	1.95E-01	3.74E-11	7.38E-11
10	2.75E-04	2.66E-01	8.15E-01	1.51E-10	2.98E-10
11	5.93E-04	1.10E+00	3.30E+00	6.00E-10	1.19E-09
12	1.23E-03	4.04E+00	1.27E+01	2.12E-09	4.20E-09
13	2.61E-03	1.47E+01	4.50E+01	7.56E-09	1.50E-08
14	5.53E-03	4.70E+01	1.44E+02	2.39E-08	4.74E-08
15	1.17E-02	1.32E+02	4.07E+02	6.67E-08	1.34E-07
16	2.48E-02	3.21E+02	9.86E+02	1.81E-07	4.86E-07
17	5.25E-02	5.88E+02	1.81E+03	3.90E-07	1.58E-06
18	1.11E-01	4.88E+02	1.50E+03	3.83E-07	2.33E-06
19	2.24E-01	2.86E+01	9.40E+01	2.97E-08	2.37E-07
20	4.51E-01	1.60E-03	5.26E-03	2.33E-12	2.27E-11
21	9.07E-01	9.23E-13	3.04E-12	2.07E-21	2.21E-20
22	1.87E+00	9.01E-26	2.86E-25	3.07E-34	3.16E-33
23	3.68E+00	4.09E-36	1.40E-35	1.68E-44	1.64E-43
24	7.41E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
25	1.49E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
26	2.58E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
27	4.47E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	7.73E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
29	1.34E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
30	2.31E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31	4.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table B.3

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 10 MV accelerator energy at position C.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	1.14E+00	7.02E-01	5.97E-10	1.31E-09
2	6.83E-07	2.54E+00	1.17E+01	1.55E-09	3.13E-09
3	1.45E-06	4.55E+00	1.40E+01	2.81E-09	5.70E-09
4	3.06E-06	5.58E+00	1.71E+01	3.42E-09	6.94E-09
5	6.48E-06	7.01E+00	2.15E+01	4.25E-09	8.60E-09
6	1.37E-05	9.01E+00	2.77E+01	5.41E-09	1.09E-08
7	2.90E-05	1.18E+01	3.63E+01	7.06E-09	1.41E-08
8	6.14E-05	1.58E+01	4.84E+01	9.36E-09	1.86E-08
9	1.30E-04	2.14E+01	6.57E+01	1.26E-08	2.49E-08
10	2.75E-04	2.93E+01	8.99E+01	1.67E-08	3.29E-08
11	5.93E-04	4.10E+01	1.23E+02	2.24E-08	4.43E-08
12	1.23E-03	5.37E+01	1.69E+02	2.82E-08	5.58E-08
13	2.61E-03	7.49E+01	2.30E+02	3.86E-08	7.64E-08
14	5.53E-03	1.01E+02	3.11E+02	5.15E-08	1.02E-07
15	1.17E-02	1.36E+02	4.18E+02	6.86E-08	1.37E-07
16	2.48E-02	1.83E+02	5.62E+02	1.03E-07	2.77E-07
17	5.25E-02	2.45E+02	7.54E+02	1.63E-07	6.60E-07
18	1.11E-01	3.25E+02	9.98E+02	2.55E-07	1.55E-06
19	2.24E-01	3.50E+02	1.15E+03	3.64E-07	2.91E-06
20	4.51E-01	2.75E+02	9.05E+02	4.00E-07	3.90E-06
21	9.07E-01	1.31E+02	4.32E+02	2.95E-07	3.14E-06
22	1.87E+00	4.63E+01	1.47E+02	1.58E-07	1.62E-06
23	3.68E+00	1.86E+01	6.33E+01	7.84E-08	7.42E-07
24	7.41E+00	4.74E+00	1.56E+01	2.74E-08	1.93E-07
25	1.49E+01	2.34E-01	7.71E-01	1.55E-09	9.63E-09
26	2.58E+01	1.73E-03	7.26E-03	1.57E-11	7.53E-11
27	4.47E+01	1.60E-05	6.73E-05	1.54E-13	7.10E-13
28	7.73E+01	1.51E-07	6.32E-07	1.53E-15	7.09E-15
29	1.34E+02	1.43E-09	6.00E-09	1.62E-17	7.18E-17
30	2.31E+02	1.36E-11	5.72E-11	2.03E-19	7.54E-19
31	4.00E+02	1.32E-13	5.56E-13	2.38E-21	8.42E-21

Table B.4

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 15 MV accelerator energy at position A.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	5.29E+01	3.27E+01	2.78E-08	6.08E-08
2	6.83E-07	1.17E+02	5.41E+02	7.15E-08	1.45E-07
3	1.45E-06	2.04E+02	6.27E+02	1.26E-07	2.56E-07
4	3.06E-06	2.41E+02	7.41E+02	1.48E-07	3.00E-07
5	6.48E-06	2.90E+02	8.91E+02	1.76E-07	3.56E-07
6	1.37E-05	3.55E+02	1.09E+03	2.13E-07	4.30E-07
7	2.90E-05	4.42E+02	1.36E+03	2.64E-07	5.28E-07
8	6.14E-05	5.57E+02	1.71E+03	3.31E-07	6.57E-07
9	1.30E-04	7.12E+02	2.18E+03	4.19E-07	8.26E-07
10	2.75E-04	9.15E+02	2.81E+03	5.21E-07	1.03E-06
11	5.93E-04	1.21E+03	3.62E+03	6.59E-07	1.30E-06
12	1.23E-03	1.48E+03	4.66E+03	7.79E-07	1.54E-06
13	2.61E-03	1.95E+03	5.99E+03	1.01E-06	1.99E-06
14	5.53E-03	2.50E+03	7.67E+03	1.27E-06	2.52E-06
15	1.17E-02	3.20E+03	9.81E+03	1.61E-06	3.22E-06
16	2.48E-02	4.11E+03	1.26E+04	2.31E-06	6.22E-06
17	5.25E-02	5.36E+03	1.65E+04	3.56E-06	1.44E-05
18	1.11E-01	7.16E+03	2.20E+04	5.62E-06	3.42E-05
19	2.24E-01	8.46E+03	2.78E+04	8.78E-06	7.02E-05
20	4.51E-01	8.20E+03	2.70E+04	1.19E-05	1.16E-04
21	9.07E-01	4.47E+03	1.47E+04	1.00E-05	1.07E-04
22	1.87E+00	1.14E+03	3.61E+03	3.87E-06	3.98E-05
23	3.68E+00	2.39E+02	8.16E+02	1.01E-06	9.57E-06
24	7.41E+00	2.92E+01	9.61E+01	1.69E-07	1.19E-06
25	1.49E+01	7.85E-01	2.58E+00	5.20E-09	3.23E-08
26	2.58E+01	4.98E-03	2.09E-02	4.53E-11	2.17E-10
27	4.47E+01	3.86E-05	1.62E-04	3.71E-13	1.71E-12
28	7.73E+01	3.09E-07	1.30E-06	3.13E-15	1.46E-14
29	1.34E+02	2.56E-09	1.08E-08	2.91E-17	1.29E-16
30	2.31E+02	2.17E-11	9.09E-11	3.23E-19	1.20E-18
31	4.00E+02	1.95E-13	8.20E-13	3.50E-21	1.24E-20

Table B.5

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 15 MV accelerator energy at position B.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	3.95E+01	2.45E+01	2.08E-08	4.55E-08
2	6.83E-07	9.16E+01	4.22E+02	5.58E-08	1.13E-07
3	1.45E-06	1.68E+02	5.16E+02	1.04E-07	2.11E-07
4	3.06E-06	2.10E+02	6.46E+02	1.29E-07	2.62E-07
5	6.48E-06	2.65E+02	8.12E+02	1.61E-07	3.25E-07
6	1.37E-05	3.34E+02	1.03E+03	2.01E-07	4.05E-07
7	2.90E-05	4.23E+02	1.30E+03	2.52E-07	5.05E-07
8	6.14E-05	5.35E+02	1.64E+03	3.17E-07	6.30E-07
9	1.30E-04	6.76E+02	2.08E+03	3.98E-07	7.85E-07
10	2.75E-04	8.47E+02	2.60E+03	4.83E-07	9.51E-07
11	5.93E-04	1.07E+03	3.22E+03	5.87E-07	1.16E-06
12	1.23E-03	1.26E+03	3.95E+03	6.60E-07	1.31E-06
13	2.61E-03	1.55E+03	4.76E+03	7.98E-07	1.58E-06
14	5.53E-03	1.84E+03	5.64E+03	9.34E-07	1.85E-06
15	1.17E-02	2.14E+03	6.58E+03	1.08E-06	2.16E-06
16	2.48E-02	2.46E+03	7.55E+03	1.38E-06	3.72E-06
17	5.25E-02	2.77E+03	8.50E+03	1.84E-06	7.44E-06
18	1.11E-01	3.02E+03	9.26E+03	2.37E-06	1.44E-05
19	2.24E-01	2.83E+03	9.30E+03	2.93E-06	2.35E-05
20	4.51E-01	2.45E+03	8.04E+03	3.56E-06	3.47E-05
21	9.07E-01	1.94E+03	6.40E+03	4.36E-06	4.65E-05
22	1.87E+00	1.58E+03	5.03E+03	5.39E-06	5.55E-05
23	3.68E+00	1.20E+03	4.10E+03	5.08E-06	4.80E-05
24	7.41E+00	4.98E+02	1.64E+03	2.88E-06	2.03E-05
25	1.49E+01	3.34E+01	1.10E+02	2.21E-07	1.37E-06
26	2.58E+01	2.61E-01	1.10E+00	2.37E-09	1.14E-08
27	4.47E+01	2.60E-03	1.09E-02	2.49E-11	1.15E-10
28	7.73E+01	2.59E-05	1.09E-04	2.62E-13	1.22E-12
29	1.34E+02	2.58E-07	1.08E-06	2.93E-15	1.30E-14
30	2.31E+02	2.57E-09	1.08E-08	3.83E-17	1.42E-16
31	4.00E+02	2.57E-11	1.08E-10	4.61E-19	1.63E-18

Table B.6

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 15 MV accelerator energy at position C.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	5.17E+02	3.20E+02	2.72E-07	5.96E-07
2	6.83E-07	9.93E+02	4.57E+03	6.04E-07	1.22E-06
3	1.45E-06	1.37E+03	4.20E+03	8.45E-07	1.72E-06
4	3.06E-06	1.26E+03	3.88E+03	7.75E-07	1.57E-06
5	6.48E-06	1.19E+03	3.64E+03	7.20E-07	1.46E-06
6	1.37E-05	1.13E+03	3.48E+03	6.81E-07	1.37E-06
7	2.90E-05	1.10E+03	3.38E+03	6.58E-07	1.32E-06
8	6.14E-05	1.09E+03	3.35E+03	6.47E-07	1.29E-06
9	1.30E-04	1.10E+03	3.37E+03	6.46E-07	1.27E-06
10	2.75E-04	1.13E+03	3.45E+03	6.41E-07	1.26E-06
11	5.93E-04	1.20E+03	3.61E+03	6.56E-07	1.30E-06
12	1.23E-03	1.22E+03	3.83E+03	6.40E-07	1.27E-06
13	2.61E-03	1.35E+03	4.14E+03	6.94E-07	1.38E-06
14	5.53E-03	1.48E+03	4.54E+03	7.52E-07	1.49E-06
15	1.17E-02	1.66E+03	5.08E+03	8.34E-07	1.67E-06
16	2.48E-02	1.91E+03	5.86E+03	1.07E-06	2.89E-06
17	5.25E-02	2.29E+03	7.02E+03	1.52E-06	6.15E-06
18	1.11E-01	2.95E+03	9.05E+03	2.31E-06	1.41E-05
19	2.24E-01	3.76E+03	1.24E+04	3.90E-06	3.12E-05
20	4.51E-01	4.80E+03	1.58E+04	6.98E-06	6.80E-05
21	9.07E-01	4.23E+03	1.39E+04	9.50E-06	1.01E-04
22	1.87E+00	2.14E+03	6.80E+03	7.29E-06	7.50E-05
23	3.68E+00	8.13E+02	2.77E+03	3.43E-06	3.25E-05
24	7.41E+00	1.63E+02	5.35E+02	9.39E-07	6.62E-06
25	1.49E+01	6.26E+00	2.06E+01	4.15E-08	2.57E-07
26	2.58E+01	4.31E-02	1.81E-01	3.92E-10	1.88E-09
27	4.47E+01	3.69E-04	1.55E-03	3.54E-12	1.63E-11
28	7.73E+01	3.22E-06	1.35E-05	3.27E-14	1.52E-13
29	1.34E+02	2.87E-08	1.21E-07	3.27E-16	1.45E-15
30	2.31E+02	2.60E-10	1.09E-09	3.87E-18	1.44E-17
31	4.00E+02	2.44E-12	1.03E-11	4.38E-20	1.55E-19

Table B.7

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 15 MV accelerator energy at position D.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	1.38E+02	8.51E+01	7.24E-08	1.58E-07
2	6.83E-07	3.05E+02	1.41E+03	1.86E-07	3.76E-07
3	1.45E-06	5.15E+02	1.58E+03	3.18E-07	6.45E-07
4	3.06E-06	5.83E+02	1.79E+03	3.58E-07	7.25E-07
5	6.48E-06	6.64E+02	2.04E+03	4.03E-07	8.15E-07
6	1.37E-05	7.62E+02	2.34E+03	4.58E-07	9.23E-07
7	2.90E-05	8.79E+02	2.70E+03	5.25E-07	1.05E-06
8	6.14E-05	1.02E+03	3.12E+03	6.04E-07	1.20E-06
9	1.30E-04	1.18E+03	3.63E+03	6.97E-07	1.37E-06
10	2.75E-04	1.37E+03	4.22E+03	7.82E-07	1.54E-06
11	5.93E-04	1.63E+03	4.89E+03	8.90E-07	1.76E-06
12	1.23E-03	1.80E+03	5.65E+03	9.44E-07	1.87E-06
13	2.61E-03	2.12E+03	6.51E+03	1.09E-06	2.16E-06
14	5.53E-03	2.43E+03	7.47E+03	1.24E-06	2.45E-06
15	1.17E-02	2.79E+03	8.56E+03	1.41E-06	2.81E-06
16	2.48E-02	3.21E+03	9.86E+03	1.81E-06	4.86E-06
17	5.25E-02	3.76E+03	1.16E+04	2.50E-06	1.01E-05
18	1.11E-01	4.57E+03	1.40E+04	3.58E-06	2.18E-05
19	2.24E-01	5.31E+03	1.75E+04	5.51E-06	4.40E-05
20	4.51E-01	6.16E+03	2.03E+04	8.96E-06	8.73E-05
21	9.07E-01	5.23E+03	1.72E+04	1.17E-05	1.25E-04
22	1.87E+00	2.39E+03	7.60E+03	8.14E-06	8.38E-05
23	3.68E+00	7.60E+02	2.59E+03	3.21E-06	3.04E-05
24	7.41E+00	1.22E+02	4.00E+02	7.02E-07	4.95E-06
25	1.49E+01	3.84E+00	1.26E+01	2.54E-08	1.58E-07
26	2.58E+01	2.51E-02	1.05E-01	2.28E-10	1.09E-09
27	4.47E+01	2.02E-04	8.49E-04	1.94E-12	8.95E-12
28	7.73E+01	1.67E-06	7.02E-06	1.69E-14	7.87E-14
29	1.34E+02	1.42E-08	5.97E-08	1.61E-16	7.13E-16
30	2.31E+02	1.23E-10	5.16E-10	1.83E-18	6.80E-18
31	4.00E+02	1.12E-12	4.72E-12	2.02E-20	7.15E-20

Table B.8

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 18 MV accelerator energy at position A.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	4.03E-01	2.49E-01	2.12E-10	4.64E-10
2	6.83E-07	1.08E+00	4.99E+00	6.60E-10	1.34E-09
3	1.45E-06	2.64E+00	8.09E+00	1.63E-09	3.30E-09
4	3.06E-06	4.56E+00	1.40E+01	2.80E-09	5.67E-09
5	6.48E-06	8.05E+00	2.47E+01	4.89E-09	9.88E-09
6	1.37E-05	1.45E+01	4.46E+01	8.72E-09	1.76E-08
7	2.90E-05	2.66E+01	8.18E+01	1.59E-08	3.18E-08
8	6.14E-05	4.95E+01	1.52E+02	2.94E-08	5.83E-08
9	1.30E-04	9.34E+01	2.87E+02	5.50E-08	1.08E-07
10	2.75E-04	1.75E+02	5.39E+02	1.00E-07	1.97E-07
11	5.93E-04	3.34E+02	1.00E+03	1.82E-07	3.60E-07
12	1.23E-03	5.86E+02	1.84E+03	3.08E-07	6.09E-07
13	2.61E-03	1.07E+03	3.29E+03	5.52E-07	1.09E-06
14	5.53E-03	1.87E+03	5.76E+03	9.53E-07	1.89E-06
15	1.17E-02	3.19E+03	9.80E+03	1.61E-06	3.22E-06
16	2.48E-02	5.30E+03	1.63E+04	2.98E-06	8.02E-06
17	5.25E-02	8.60E+03	2.64E+04	5.71E-06	2.31E-05
18	1.11E-01	1.32E+04	4.05E+04	1.04E-05	6.30E-05
19	2.24E-01	1.52E+04	5.01E+04	1.58E-05	1.26E-04
20	4.51E-01	1.20E+04	3.93E+04	1.74E-05	1.69E-04
21	9.07E-01	7.08E+03	2.33E+04	1.59E-05	1.69E-04
22	1.87E+00	4.16E+03	1.32E+04	1.42E-05	1.46E-04
23	3.68E+00	2.91E+03	9.91E+03	1.23E-05	1.16E-04
24	7.41E+00	1.25E+03	4.12E+03	7.24E-06	5.11E-05
25	1.49E+01	9.17E+01	3.02E+02	6.08E-07	3.77E-06
26	2.58E+01	7.38E-01	3.10E+00	6.71E-09	3.22E-08
27	4.47E+01	7.58E-03	3.18E-02	7.28E-11	3.36E-10
28	7.73E+01	7.78E-05	3.27E-04	7.88E-13	3.67E-12
29	1.34E+02	7.95E-07	3.34E-06	9.04E-15	4.00E-14
30	2.31E+02	8.08E-09	3.39E-08	1.20E-16	4.47E-16
31	4.00E+02	8.14E-11	3.42E-10	1.46E-18	5.18E-18

Table B.9

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 18 MV accelerator energy at position B.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	6.23E+00	3.85E+00	3.28E-09	7.17E-09
2	6.83E-07	1.58E+01	7.27E+01	9.61E-09	1.94E-08
3	1.45E-06	3.39E+01	1.04E+02	2.09E-08	4.25E-08
4	3.06E-06	5.07E+01	1.56E+02	3.11E-08	6.30E-08
5	6.48E-06	7.65E+01	2.35E+02	4.64E-08	9.39E-08
6	1.37E-05	1.17E+02	3.58E+02	7.01E-08	1.41E-07
7	2.90E-05	1.79E+02	5.51E+02	1.07E-07	2.14E-07
8	6.14E-05	2.76E+02	8.47E+02	1.64E-07	3.25E-07
9	1.30E-04	4.27E+02	1.31E+03	2.51E-07	4.95E-07
10	2.75E-04	6.52E+02	2.00E+03	3.71E-07	7.32E-07
11	5.93E-04	1.00E+03	3.01E+03	5.47E-07	1.08E-06
12	1.23E-03	1.42E+03	4.44E+03	7.43E-07	1.47E-06
13	2.61E-03	2.08E+03	6.38E+03	1.07E-06	2.12E-06
14	5.53E-03	2.91E+03	8.94E+03	1.48E-06	2.94E-06
15	1.17E-02	3.96E+03	1.22E+04	2.00E-06	4.00E-06
16	2.48E-02	5.23E+03	1.61E+04	2.94E-06	7.92E-06
17	5.25E-02	6.66E+03	2.05E+04	4.42E-06	1.79E-05
18	1.11E-01	7.91E+03	2.43E+04	6.21E-06	3.78E-05
19	2.24E-01	7.34E+03	2.41E+04	7.62E-06	6.09E-05
20	4.51E-01	5.35E+03	1.76E+04	7.78E-06	7.58E-05
21	9.07E-01	3.48E+03	1.15E+04	7.81E-06	8.32E-05
22	1.87E+00	2.77E+03	8.79E+03	9.42E-06	9.70E-05
23	3.68E+00	2.57E+03	8.75E+03	1.08E-05	1.03E-04
24	7.41E+00	1.42E+03	4.68E+03	8.22E-06	5.80E-05
25	1.49E+01	1.25E+02	4.10E+02	8.26E-07	5.13E-06
26	2.58E+01	1.04E+00	4.38E+00	9.48E-09	4.54E-08
27	4.47E+01	1.12E-02	4.72E-02	1.08E-10	4.97E-10
28	7.73E+01	1.20E-04	5.05E-04	1.22E-12	5.67E-12
29	1.34E+02	1.28E-06	5.36E-06	1.45E-14	6.41E-14
30	2.31E+02	1.34E-08	5.64E-08	2.00E-16	7.43E-16
31	4.00E+02	1.39E-10	5.82E-10	2.48E-18	8.80E-18

Table B.10

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 18 MV accelerator energy at position C.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	1.01E+02	6.23E+01	5.29E-08	1.16E-07
2	6.83E-07	2.07E+02	9.55E+02	1.26E-07	2.55E-07
3	1.45E-06	3.27E+02	1.00E+03	2.02E-07	4.10E-07
4	3.06E-06	3.52E+02	1.08E+03	2.16E-07	4.38E-07
5	6.48E-06	3.85E+02	1.18E+03	2.34E-07	4.72E-07
6	1.37E-05	4.28E+02	1.31E+03	2.57E-07	5.18E-07
7	2.90E-05	4.83E+02	1.48E+03	2.89E-07	5.78E-07
8	6.14E-05	5.55E+02	1.70E+03	3.30E-07	6.55E-07
9	1.30E-04	6.49E+02	1.99E+03	3.82E-07	7.54E-07
10	2.75E-04	7.71E+02	2.37E+03	4.39E-07	8.65E-07
11	5.93E-04	9.50E+02	2.85E+03	5.19E-07	1.03E-06
12	1.23E-03	1.11E+03	3.49E+03	5.84E-07	1.16E-06
13	2.61E-03	1.41E+03	4.34E+03	7.27E-07	1.44E-06
14	5.53E-03	1.78E+03	5.47E+03	9.05E-07	1.80E-06
15	1.17E-02	2.29E+03	7.03E+03	1.15E-06	2.31E-06
16	2.48E-02	3.04E+03	9.34E+03	1.71E-06	4.61E-06
17	5.25E-02	4.27E+03	1.31E+04	2.83E-06	1.15E-05
18	1.11E-01	6.56E+03	2.01E+04	5.15E-06	3.13E-05
19	2.24E-01	1.00E+04	3.30E+04	1.04E-05	8.33E-05
20	4.51E-01	1.39E+04	4.57E+04	2.02E-05	1.97E-04
21	9.07E-01	1.02E+04	3.36E+04	2.29E-05	2.44E-04
22	1.87E+00	2.87E+03	9.11E+03	9.76E-06	1.01E-04
23	3.68E+00	6.03E+02	2.05E+03	2.54E-06	2.41E-05
24	7.41E+00	7.74E+01	2.55E+02	4.47E-07	3.15E-06
25	1.49E+01	2.27E+00	7.48E+00	1.51E-08	9.35E-08
26	2.58E+01	1.50E-02	6.29E-02	1.36E-10	6.52E-10
27	4.47E+01	1.21E-04	5.08E-04	1.16E-12	5.36E-12
28	7.73E+01	1.01E-06	4.25E-06	1.02E-14	4.76E-14
29	1.34E+02	8.68E-09	3.65E-08	9.87E-17	4.36E-16
30	2.31E+02	7.58E-11	3.18E-10	1.13E-18	4.19E-18
31	4.00E+02	7.00E-13	2.94E-12	1.26E-20	4.45E-20

Table B.11

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 20 MV accelerator energy at position A.

BIN	ENERGY	FLUENCE	FLUENCE	DOSE	DOSE
NO.	MAX (MEV)	CM ⁻²	CM ⁻² LETH ⁻¹	(REM)	EQUIVALENT (RAD)
1	4.14E-07	2.25E+01	1.39E+01	1.18E-08	2.59E-08
2	6.83E-07	5.13E+01	2.36E+02	3.12E-08	6.32E-08
3	1.45E-06	9.59E+01	2.94E+02	5.92E-08	1.20E-07
4	3.06E-06	1.24E+02	3.82E+02	7.63E-08	1.55E-07
5	6.48E-06	1.64E+02	5.04E+02	9.96E-08	2.01E-07
6	1.37E-05	2.21E+02	6.78E+02	1.33E-07	2.68E-07
7	2.90E-05	3.03E+02	9.30E+02	1.81E-07	3.62E-07
8	6.14E-05	4.21E+02	1.29E+03	2.50E-07	4.97E-07
9	1.30E-04	5.96E+02	1.83E+03	3.51E-07	6.92E-07
10	2.75E-04	8.49E+02	2.61E+03	4.84E-07	9.53E-07
11	5.93E-04	1.24E+03	3.73E+03	6.79E-07	1.34E-06
12	1.23E-03	1.70E+03	5.35E+03	8.95E-07	1.77E-06
13	2.61E-03	2.49E+03	7.65E+03	1.28E-06	2.54E-06
14	5.53E-03	3.56E+03	1.09E+04	1.81E-06	3.59E-06
15	1.17E-02	5.08E+03	1.56E+04	2.56E-06	5.12E-06
16	2.48E-02	7.29E+03	2.24E+04	4.11E-06	1.10E-05
17	5.25E-02	1.07E+04	3.27E+04	7.07E-06	2.86E-05
18	1.11E-01	1.59E+04	4.89E+04	1.25E-05	7.60E-05
19	2.24E-01	2.07E+04	6.81E+04	2.15E-05	1.72E-04
20	4.51E-01	2.15E+04	7.06E+04	3.12E-05	3.04E-04
21	9.07E-01	1.37E+04	4.51E+04	3.07E-05	3.27E-04
22	1.87E+00	5.02E+03	1.60E+04	1.71E-05	1.76E-04
23	3.68E+00	1.62E+03	5.53E+03	6.85E-06	6.49E-05
24	7.41E+00	3.12E+02	1.03E+03	1.81E-06	1.27E-05
25	1.49E+01	1.21E+01	3.98E+01	8.02E-08	4.98E-07
26	2.58E+01	8.41E-02	3.53E-01	7.65E-10	3.66E-09
27	4.47E+01	7.25E-04	3.04E-03	6.96E-12	3.21E-11
28	7.73E+01	6.38E-06	2.68E-05	6.46E-14	3.01E-13
29	1.34E+02	5.72E-08	2.41E-07	6.51E-16	2.88E-15
30	2.31E+02	5.19E-10	2.18E-09	7.73E-18	2.87E-17
31	4.00E+02	4.89E-12	2.05E-11	8.77E-20	3.11E-19

Table B.12

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 20 MV accelerator energy at position B.

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	1.03E+02	6.36E+01	5.41E-08	1.18E-07
2	6.83E-07	2.23E+02	1.03E+03	1.36E-07	2.75E-07
3	1.45E-06	3.74E+02	1.15E+03	2.31E-07	4.68E-07
4	3.06E-06	4.23E+02	1.30E+03	2.59E-07	5.26E-07
5	6.48E-06	4.87E+02	1.49E+03	2.95E-07	5.97E-07
6	1.37E-05	5.70E+02	1.75E+03	3.43E-07	6.91E-07
7	2.90E-05	6.80E+02	2.09E+03	4.06E-07	8.12E-07
8	6.14E-05	8.22E+02	2.52E+03	4.88E-07	9.69E-07
9	1.30E-04	1.01E+03	3.10E+03	5.94E-07	1.17E-06
10	2.75E-04	1.25E+03	3.84E+03	7.12E-07	1.40E-06
11	5.93E-04	1.60E+03	4.79E+03	8.72E-07	1.72E-06
12	1.23E-03	1.92E+03	6.02E+03	1.01E-06	1.99E-06
13	2.61E-03	2.47E+03	7.59E+03	1.27E-06	2.52E-06
14	5.53E-03	3.13E+03	9.61E+03	1.59E-06	3.15E-06
15	1.17E-02	3.99E+03	1.22E+04	2.01E-06	4.02E-06
16	2.48E-02	5.17E+03	1.59E+04	2.91E-06	7.83E-06
17	5.25E-02	6.92E+03	2.13E+04	4.60E-06	1.86E-05
18	1.11E-01	9.79E+03	3.01E+04	7.68E-06	4.68E-05
19	2.24E-01	1.28E+04	4.20E+04	1.33E-05	1.06E-04
20	4.51E-01	1.36E+04	4.45E+04	1.97E-05	1.92E-04
21	9.07E-01	6.80E+03	2.24E+04	1.53E-05	1.63E-04
22	1.87E+00	1.23E+03	3.90E+03	4.18E-06	4.30E-05
23	3.68E+00	1.84E+02	6.26E+02	7.75E-07	7.34E-06
24	7.41E+00	1.71E+01	5.62E+01	9.86E-08	6.95E-07
25	1.49E+01	3.88E-01	1.28E+00	2.57E-09	1.60E-08
26	2.58E+01	2.39E-03	1.00E-02	2.17E-11	1.04E-10
27	4.47E+01	1.79E-05	7.51E-05	1.72E-13	7.91E-13
28	7.73E+01	1.39E-07	5.84E-07	1.41E-15	6.56E-15
29	1.34E+02	1.12E-09	4.73E-09	1.28E-17	5.65E-17
30	2.31E+02	9.31E-12	3.91E-11	1.39E-19	5.15E-19
31	4.00E+02	8.31E-14	3.49E-13	1.49E-21	5.28E-21

Table B.13

The BUNKI code output results of the TLD/Bonner Sphere Spectrometer (BSS) data for the 20 MV accelerator energy at position C ..

BIN NO.	ENERGY MAX (MEV)	FLUENCE CM ⁻²	FLUENCE CM ⁻² LETH ⁻¹	DOSE (REM)	DOSE EQUIVALENT (RAD)
1	4.14E-07	2.15E+01	1.33E+01	1.13E-08	2.48E-08
2	6.83E-07	5.05E+01	2.33E+02	3.07E-08	6.22E-08
3	1.45E-06	9.73E+01	2.99E+02	6.01E-08	1.22E-07
4	3.06E-06	1.30E+02	3.98E+02	7.96E-08	1.61E-07
5	6.48E-06	1.76E+02	5.39E+02	1.07E-07	2.15E-07
6	1.37E-05	2.41E+02	7.39E+02	1.45E-07	2.91E-07
7	2.90E-05	3.34E+02	1.03E+03	1.99E-07	3.99E-07
8	6.14E-05	4.67E+02	1.43E+03	2.77E-07	5.51E-07
9	1.30E-04	6.61E+02	2.03E+03	3.90E-07	7.68E-07
10	2.75E-04	9.36E+02	2.87E+03	5.33E-07	1.05E-06
11	5.93E-04	1.35E+03	4.06E+03	7.39E-07	1.46E-06
12	1.23E-03	1.82E+03	5.72E+03	9.55E-07	1.89E-06
13	2.61E-03	2.59E+03	7.96E+03	1.34E-06	2.64E-06
14	5.53E-03	3.58E+03	1.10E+04	1.82E-06	3.61E-06
15	1.17E-02	4.91E+03	1.51E+04	2.48E-06	4.96E-06
16	2.48E-02	6.71E+03	2.06E+04	3.78E-06	1.02E-05
17	5.25E-02	9.22E+03	2.83E+04	6.12E-06	2.48E-05
18	1.11E-01	1.27E+04	3.91E+04	1.00E-05	6.08E-05
19	2.24E-01	1.54E+04	5.08E+04	1.60E-05	1.28E-04
20	4.51E-01	1.63E+04	5.34E+04	2.36E-05	2.30E-04
21	9.07E-01	1.26E+04	4.16E+04	2.83E-05	3.02E-04
22	1.87E+00	6.40E+03	2.03E+04	2.18E-05	2.24E-04
23	3.68E+00	2.56E+03	8.71E+03	1.08E-05	1.02E-04
24	7.41E+00	5.42E+02	1.78E+03	3.13E-06	2.21E-05
25	1.49E+01	2.15E+01	7.07E+01	1.42E-07	8.84E-07
26	2.58E+01	1.48E-01	6.23E-01	1.35E-09	6.46E-09
27	4.47E+01	1.27E-03	5.34E-03	1.22E-11	5.64E-11
28	7.73E+01	1.11E-05	4.67E-05	1.13E-13	5.24E-13
29	1.34E+02	9.89E-08	4.16E-07	1.12E-15	4.97E-15
30	2.31E+02	8.91E-10	3.74E-09	1.33E-17	4.94E-17
31	4.00E+02	8.35E-12	3.51E-11	1.50E-19	5.31E-19

APPENDIX C

Bubble Detector Spectrometer Results Using Spectral Stripping

Appendix A contains the the spectral stripping method outputs of the calculated spectra using the Bubble detector Spectrometer (BDS) data. Spectra for all four accelerators and all measured positions are included. The first column of the table is the energy bin structure from 1 to 6 corresponding to the six energy threshold detectors used. The second column is the calculated fluence for the 10 MV LINAC. The third column is the calculated fluence per bin for the 15 MV LINAC, and the fourth and fifth columns are for the 18 and 20 MV LINACS, respectively. Data in this table is normalized to 1 Gy of x-ray delivered by the accelerator at isocenter.

Table C.1

Neutron fluence ($\text{cm}^{-2} \text{Gy}^{-1}$) for the four LINACs, measured using the Bubble Detector Spectrometer (BDS) spectral stripping method.

Position A

E (MeV)	10 MV	15 MV	18 MV	20 MV
0.01	1.26E+06	1.14E+07	3.42E+07	3.30E+07
0.1	3.00E+04	4.90E+05	8.69E+05	4.38E+05
0.6	9.41E+04	1.06E+06	3.16E+06	3.45E+06
1	4.83E+03	2.44E+05	5.90E+05	9.18E+05
2.5	1.56E+02	4.26E+04	1.45E+05	2.10E+05
10	0.00E+00	1.64E+00	5.43E+02	4.47E+03

Position B

E (MeV)	10 MV	15 MV	18 MV	20 MV
0.01	8.46E+05	7.74E+06	2.58E+07	2.41E+07
0.1	5.58E+04	1.31E+06	6.92E+05	1.20E+05
0.6	6.61E+04	1.03E+06	2.14E+06	3.34E+06
1	3.52E+03	2.22E+05	6.27E+05	8.23E+05
2.5	1.89E+02	3.60E+04	1.20E+05	1.83E+05
10	0.00E+00	1.21E+02	7.71E+02	5.34E+03

Position C

E (MeV)	10 MV	15 MV	18 MV	20 MV
0.01	1.04E+06	9.04E+06	3.50E+07	3.79E+07
0.1	1.37E+04	0.00E+00	1.06E+06	4.50E+04
0.6	9.95E+04	1.48E+06	3.34E+06	4.45E+05
1	5.21E+03	1.84E+05	4.56E+05	7.75E+05
2.5	1.61E+02	2.19E+04	8.56E+04	1.59E+05
10	0.00E+00	9.08E+01	5.23E+02	4.58E+03

Position D

E (MeV)	10 MV	15 MV	18 MV	20 MV
0.01	1.09E+06	1.36E+07	4.01E+07	3.82E+07
0.1	2.17E+04	1.74E+05	9.85E+05	7.52E+05
0.6	9.45E+04	1.60E+06	3.90E+06	5.13E+06
1	6.63E+03	2.70E+05	6.48E+05	1.09E+06
2.5	1.97E+02	2.73E+04	1.07E+05	1.90E+05
10	0.00E+00	3.31E+01	2.02E+02	6.13E+03

APPENDIX D

Bubble Detector Spectrometer Spectra Using BUNKI

The BUNKI output of the Bubble detector spectrometer data plotted twice. The first as a function of position for each of the accelerators' energies used in this study. The second as function of accelerator energy for each of the position.

Figure D.1. Neutron fluence for the 10 MV accelerator, measured using the BDS-BUNKI method. Digital data are presented in tables in appendix A.

Figure D.2. Neutron fluence for the 15 MV accelerator, measured using the BDS-BUNKI method. Digital data are presented in tables in appendix A.

Figure D.3. Neutron fluence for the 18 MV accelerator, measured using the BDS-BUNKI method. Digital data are presented in tables in appendix A.

Figure D.4. Neutron fluence for the 20 MV accelerator, measured with the BDS-BUNKI method. Digital data are presented in tables in appendix A.

Figure D.5. Neutron fluence for the four accelerators at position A, measured using the BDS-BUNKI method. Digital data are presented in tables in appendix A.

Figure D.6. Neutron fluence for the four accelerators at position B, measured using the BDS-BUNKI method. Digital data are presented in tables in appendix A.

Figure D.7. Neutron fluence for the four accelerators at position C, measured using the BDS-BUNKI method. Digital data are presented in tables in appendix A.

Figure D.8. Neutron fluence for the four accelerators at position D, measured using the BDS-BUNKI method. Digital data are presented in tables in appendix A.

APPENDIX E

Inter-Method Comparison of Neutron Spectra and Other Dosimetric Quantities

Fluence as a function of accelerator energy plotted for the four measurement positions for the BDS BUNKI outputs. The dose equivalent as a function of accelerator energy for all positions. These plots are based on measurements described in chapter 5.

Figure E.1. Neutron fluence [$\text{cm}^{-2} \text{Gy}^{-1}$] as a function of measurement position, using BDS-BUNKI method. Digital data are presented in tables 5.1 through 5.4 in chapter V.

Figure E.2. Neutron dose equivalent [$\text{cm}^{-2} \text{Gy}^{-1}$] as a function of measurement position, using BDS-BUNKI method. Digital data are presented in tables 5.1 through 5.4 in chapter V.

Figure E.3. Neutron fluence [$\text{cm}^{-2} \text{Gy}^{-1}$] as a function of measurement position, using the the fluence moderator. Digital data are presented in tables 5.1 through 5.4 in chapter V.

Figure E.4. Neutron dose equivalent [Sv Gy⁻¹] as a function of measurement position, using the A-B remmeter. Digital data are presented in tables 5.1 through 5.4 in chapter V.

Figure E.5. Inter-method comparison of the neutron fluence [cm⁻² Gy⁻¹] for measurement position A. Digital data are presented in tables 5.1 through 5.4 in chapter V.

Figure E.6. Inter-method comparison of neutron dose equivalent [Sv Gy⁻¹] for measurement position A. Digital data are presented in tables 5.1 through 5.4 in chapter V.

Figure E.7. Inter-method comparison of the neutron fluence [$\text{cm}^{-2} \text{Gy}^{-1}$] for measurement position B. Digital data are presented in tables 5.1 through 5.4 in chapter V.

Figure E.8. Inter-method comparison of neutron dose equivalent [Sv Gy⁻¹] for measurement position B. Digital data are presented in tables 5.1 through 5.4 in chapter V.

Figure E.9. Inter-method comparison of the neutron fluence [$\text{cm}^{-2} \text{Gy}^{-1}$] for measurement position C. Digital data are presented in tables 5.1 through 5.4 in chapter V.

Figure E.10. Inter-method comparison of neutron dose equivalent [Sv Gy⁻¹] for measurement position C. Digital data are presented in tables 5.1 through 5.4 in chapter V.