

# Experimental Confirmation of an Improved Neutron Dosimeter Using Superheated Liquid Drops

by

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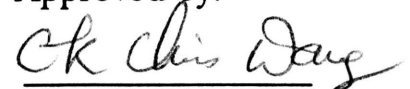
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## 1.0 Introduction

The neutron has made a revolutionary impact both directly and indirectly on science and technology since its discovery by Chadwick<sup>1</sup> in 1932. Neutrons are mainly from nuclear reactors, particle accelerator facilities, and isotopic sources such as  $^{252}\text{Cf}$ <sup>2</sup> and  $\text{Pu(Be)}$ <sup>3</sup>. The applications of neutrons include power generation, fundamental research on material properties, cancer therapies, and industrial imaging. Neutrons have been recognized as a high-LET radiation of which per unit absorbed dose is more effective than that of the low-LET radiations (e.g.  $\beta$  and  $\gamma$  rays) are in causing biological damage (e.g. cancer) to human. The increasing use of neutrons thus has raised great concern about the cancer risks that workers and general publics are subjected to. The biological effects caused by neutrons have been studied quite extensively in the past few decades, and much has been learned. Despite the wide use of neutrons and the increased human health concern, and in contrary to the increased knowledge about the biological effects due to neutrons, the techniques used to monitor human exposure to neutrons are still quite primitive and inaccurate.

There are, in general, two types of neutron dosimeters in use, which are categorized based on their applications: 1) personnel dosimeters; 2) area monitors. Personnel neutron dosimeters are passive devices used to collect and record neutron doses to persons. These devices operate in a variety of ways, and are described as follows:

- 1) The nuclear track type A (NTA) which detects the individual recoil proton tracks<sup>4,5,7,8,11,12</sup> in a thin photographic emulsion;

- 2) The thermoluminescent albedo dosimeter (TLD), which uses  ${}^6\text{Li}(n,\alpha)$  reaction in  $\text{LiF}^{6,9,10}$  to detect neutrons.
- 3) The track etch film, which uses either allyl diglycol carbonate (CR-39)<sup>31,32</sup> or polycarbonate plastic<sup>33,34</sup> to record neutron-induced charged particle tracks;  
and most recently,
- 4) The superheated drop detector (SDD)<sup>15</sup>, which uses superheated liquid drops in gel or polymer to record neutron-induced recoil ions.

Among these four types of devices, SDD holds the greatest promise as the personnel neutron dosimeter because of the following reasons:

- 1) The SDD provides instant reading;
- 2) The SDD's response to neutrons can be made reasonably dose-equivalent.
- 3) The SDD's efficiency for neutrons is quite high, and it is capable to record a neutron dose equivalent as low as 1  $\mu\text{Sv}$ .

The other three devices lack at least one of the above qualities.

Area neutron dose monitors include moderated remmeters<sup>37,38</sup> (MR), and tissue equivalent proportional counter<sup>39</sup> (TEPC). The MR consists of a slow neutron detector (e.g. a  $\text{LiI}$  scintillator or a  $\text{BF}_3$  proportional counter) surrounded with a thick (10~15cm) polyethylene moderator. The polyethylene moderator is used to shape the neutron response function of the slow neutron detector to make it more dose-equivalent. The TEPC is a hollow sphere of thin tissue-equivalent plastic walls filled with methane-based tissue gas. The gas space of a TEPC simulates a solid piece of tissue with size of  $\sim 1 \mu\text{m}$ .

TEPC measures the event-size spectrum (ESS) in keV/ $\mu\text{m}$  using a multichannel analyzer (MCA). A dose-equivalent is then calculated based on the product of ESS and the quality factors associated with the various sizes of events.

Generally speaking, MR is heavy ( $>30$  lbs), and the degree of dose-equivalence of its neutron response is rather poor. However, MR does provide instant reading (in  $\mu\text{Sv/hr}$ ), which is quite useful as an area survey meter. TEPC may weigh less, but it requires excessive data acquisition and processing to obtain the dose-equivalent value.

In this study, we experimentally investigated the neutron response function of a dosimeter which is based on a SDD-100<sup>35</sup> surrounded with 2.54 cm of polyethylene. Lo and Apfel<sup>23</sup> has calculated and confirmed with measurement the neutron response function of a SDD-100. Wang<sup>30</sup> later did a thorough Monte Carlo calculation to include the neutron response function of a SDD-100 which is surrounded with various thicknesses of polyethylene. The calculated results suggest that the neutron response function of a SDD-100 surrounded with 2.54 cm of polyethylene is significantly better in dose equivalence than that of a bare SDD-100. The major task of this thesis study was to experimentally verify the neutron response function of such a polyethylene-moderated SDD-100 dosimeter.

Chapter 2 provides detailed description of a SDD, the theory, and the neutron response function of the SDD-100 calculated with Monte Carlo techniques<sup>27</sup>.

Chapter 3 describes the rationale, equipment set-ups, and measurement techniques of the experiment.

Chapter 4 presents the experimental results and its comparison with that of calculations.

Chapter 5 gives the conclusions and suggestions for further work.

## 2.0 The Superheated Drop Detector

### 2.1 Introduction

It is well known that a liquid can be superheated without boiling. In 1952 Glaser<sup>16</sup>, the inventor of the bubble chamber, observed that radiation could cause bubble formation in a superheated liquid. In 1958 Seitz<sup>17</sup> introduced the so called "Thermal Spike Theory" as the theoretical explanation of Glaser's observation. Using the same principle as the bubble chamber, Apfel<sup>13</sup> invented a new kind of neutron detector, the Superheated Drop Detector(SDD). The SDD, as shown in Fig. 1, is composed of a large number of superheated liquid drops uniformly dispersed in a soft gel medium. Similar products using firm polymer to hold the superheated liquid drops have also been developed<sup>29</sup>. Some properties of the SDD material are shown in Table 1.

A vapor bubble may be formed when recoil ion(s) from a neutron interaction deposit enough energy in a liquid drop. The formation of bubble from a liquid drop usually does not trigger the adjacent drops to form bubbles. Each liquid drop is thus a miniature bubble chamber, which is continuously sensitive to neutron interactions until triggered. The bubble rate can then serve as a measure of neutron intensity.

SDD have been developed for personnel neutron dosimetry, area monitoring and neutron spectrometry. These SDDs are insensitive to gamma rays. Very recently, however, gamma-ray sensitive SDD<sup>40</sup> has also been developed.

**Table 1 Properties of the SDD Materials**

| Trade Name   | Chemical Formula                               | Boiling Point (°C)<br>(1 atm) | Vapor Pressure (atm)<br>(24 °C) | Density of liquid (g/cm <sup>3</sup> )<br>(24 °C) | Minimum energies for nucleation (keV) |
|--------------|------------------------------------------------|-------------------------------|---------------------------------|---------------------------------------------------|---------------------------------------|
| Freon - 12   | CCl <sub>2</sub> F <sub>2</sub>                | -29.8                         | 5.8                             | 1.3                                               | 14                                    |
| Freon - 14   | C <sub>2</sub> Cl <sub>2</sub> F <sub>4</sub>  | 3.5                           | 4.9                             | 1.5                                               | 515                                   |
| Freon - 142B | C <sub>2</sub> H <sub>3</sub> ClF <sub>2</sub> | -9.3                          | 3.0                             | 1.1                                               | 117                                   |
| Isobutane    | C <sub>4</sub> H <sub>10</sub>                 | -11.7                         | 3.1                             | 0.7                                               | 92                                    |

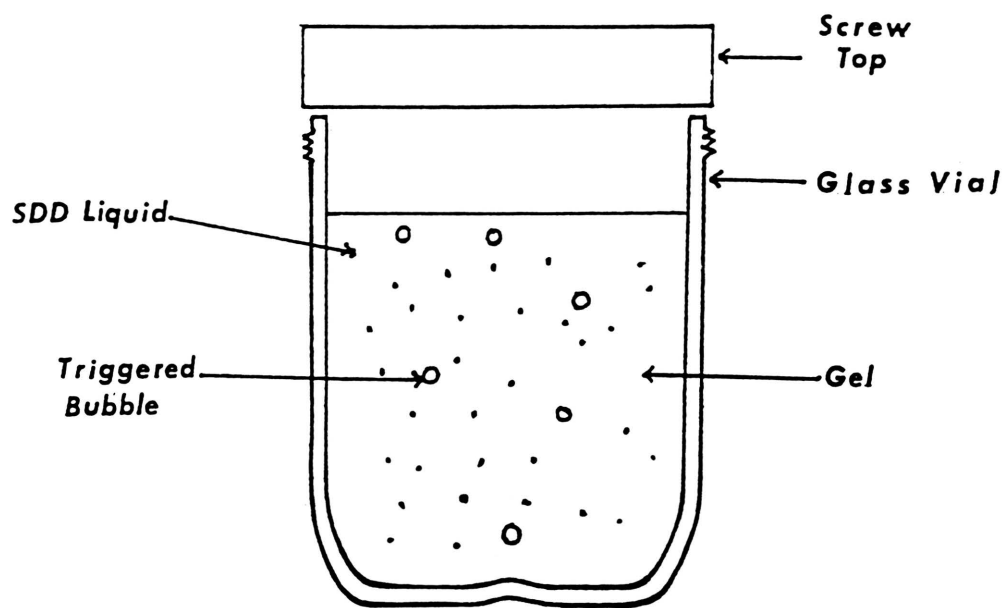


Figure 1. Schematic diagram of SDD detector.



## 2.2 Theory of Bubble Nucleation

According to the classical theory of bubble nucleation, bubble nucleation occurs in a superheated liquid only when a vapor embryo of minimum size is achieved. This minimum size vapor embryo is called the "critical radius" ( $R_c$ ). Vapor embryos less than the size of the critical bubble are unstable and tend to collapse<sup>19,49</sup>.

At this critical size, the work needed for vapor to expand equals to the change of surface tension at the vapor-liquid interfaces.

That is,

$$(P_v - P) dV = \gamma dA \quad (2.1)$$

where:  $\gamma$  = surface tension;

$A$  = area of surface of bubble;

$V$  = volume occupied by the bubble;

$P_v$  = pressure of gas;

$P$  = pressure being applied to the detector.

To minimize surface tension(energy)<sup>22</sup> bubble will take a spherical form. For a spherical bubble,  $dA/dV = 2/R_c$ .

Equation 2.1, thus becomes

$$R_c = \frac{2\gamma}{\Delta P} \quad (2.2)$$

where:  $R_c$  = the critical radius

$\Delta P$  = the variation of pressures between internal bubble pressure and externally applied pressure( $P_v-P$ ).

According to the "thermal spike theory"<sup>17</sup>, the critical bubble cannot be formed without work being done on the system. The minimum reversible work( $W_{\min}$ )<sup>20</sup> required to generate a critical bubble is given by:

$$W_{\min} = (4\pi R_c^2 \gamma - \frac{4}{3}\pi R_c^3 \Delta P) \quad (2.3)$$

Substituting equation (2.2) into equation (2.3), it becomes

$$W_{\min} = \frac{16\pi\gamma^3}{3(\Delta P)^2} \quad (2.4)$$

In reality, from experimental observation<sup>25</sup>, only a very small fraction ( $\eta=3\%\sim 6\%$ ) of the energy deposited in a critical diameter ( $2R_c$ ) can be used to form a critical bubble. The typical values of  $\eta$  for various types of Freons are shown in Fig. 2. In other words, the radiation-induced nucleation is a very inefficient process. The low efficiency may be understood by considering the dynamic factors of bubble formation<sup>24</sup>. Immediately after a (neutron, charge particle) reaction occurred in the superheated liquid drop, a strong shock wave (which is generated due to the local heating) very quickly diffuses the heat outward, and therefore, only a small percentage of the deposited energy is available for bubble formation.

The actual minimum energy,  $E_{\min}$  required for bubble formation, is thus much higher than  $W_{\min}$  and can be expressed by

$$E_{\min} = \frac{W_{\min}}{\eta} \quad (2.5)$$

It means that the recoil nuclei must have energy greater than  $E_{\min}$  in order to trigger bubble in a superheated liquid. More strictly, energy greater than  $E_{\min}$  must be

deposited within a critical diameter ( $2R_c$ ).

That is,

$$\int_0^{2R_c} \frac{dE_i}{dx} dx \geq E_{\min} \quad (2.6)$$

Where  $dE_i/dx$  is the stopping power for the recoiled ions. Fig. 3 shows the values of  $dE_i/dx$  for C, F, and Cl in Freon-12.

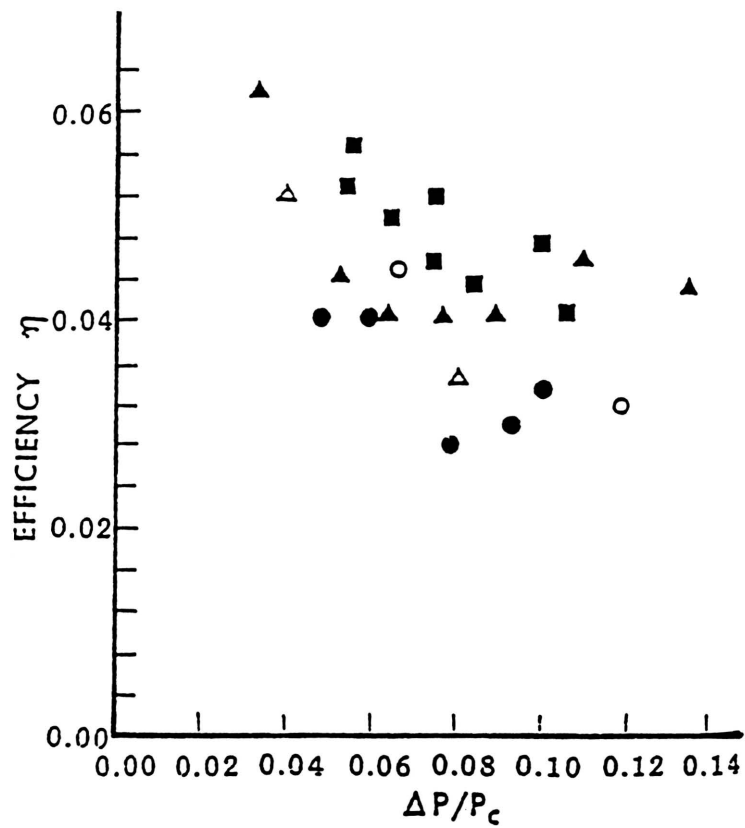


Figure 2. Efficiency factor in radiation induced nucleation.

• n Pentane      ▲ Freon      ■ Freon-113  
 ○ Isobutane      △ Freon-114

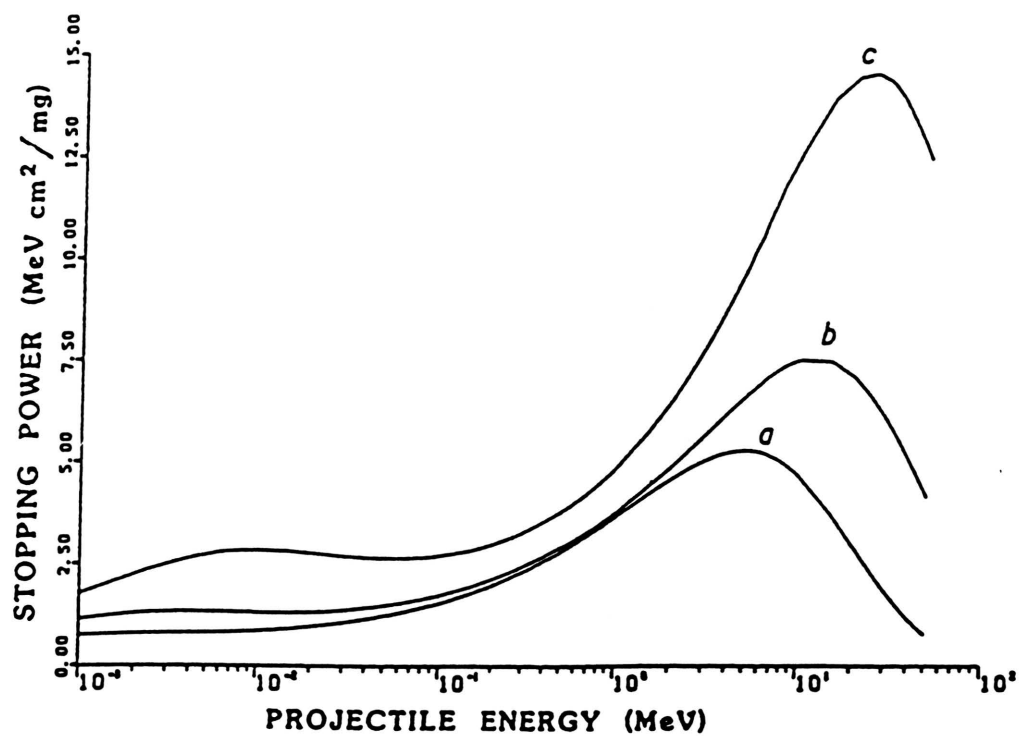


Figure 3. Stopping power of relevant projectiles in liquids of SDD-100 (Freon-12). a) Carbon b) Fluorine c) Chlorine

### 2.3 The Response Function of SDD-100

The SDD-100 which uses Freon-12( $\text{CCl}_2\text{F}_2$ , a Dupont trade mark name) for the superheated drops, is the most widely used neutron dosimeter because it was claimed<sup>35</sup> that the neutron response function of such a dosimeter is nearly dose equivalent.

Bubbles in a SDD-100 are triggered with two different types of neutron interaction: the elastic collision with C, F, and Cl nuclei, and the  $^{35}\text{Cl}(n,p)^{35}\text{S}$  reaction. In an elastic collision, the maximum energy that a recoil nucleus may acquire from a neutron is given by

$$E_{\max} = \frac{4AE_n}{(A+1)^2} \quad (2.7)$$

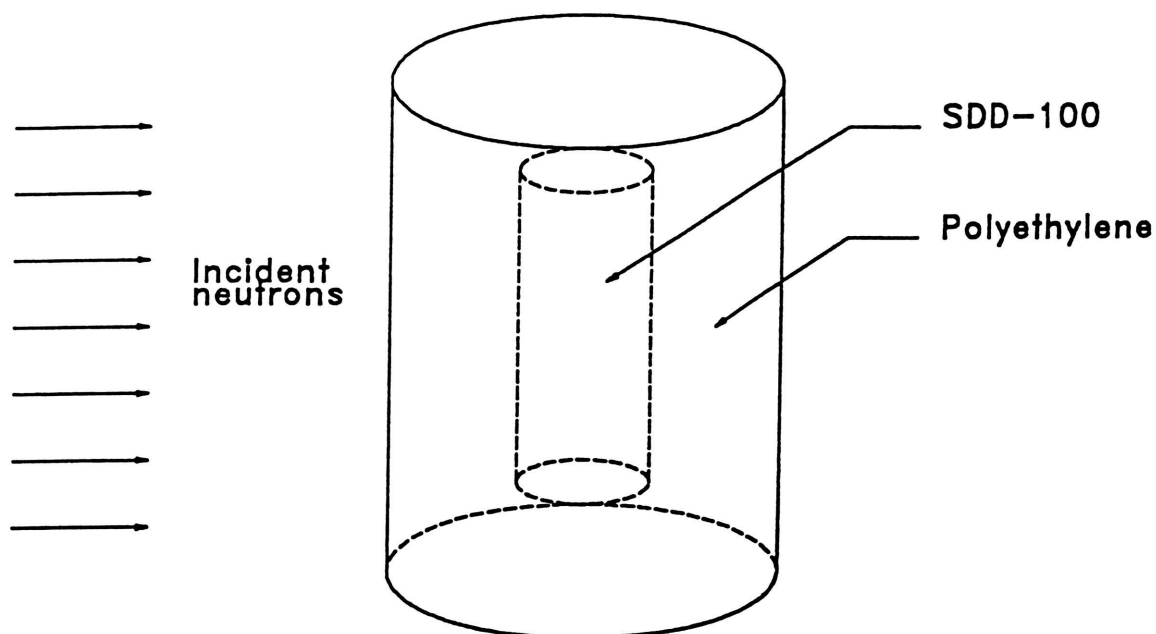
where:  $A$  = the mass number of the nucleus.

$E_n$  = the energy incident of neutron.

One also may assume that the energies of a recoil nuclei is uniformly distributed between 0 and  $E_{\max}$ . Therefore, the probability( $\mathcal{P}_1$ ) for a recoil nucleus to trigger bubble can be evaluated as

$$\mathcal{P}_1 = \frac{(E_{\max} - E_{\min})}{E_{\max}} \quad (2.8)$$

In the  $^{35}\text{Cl}(n,p)^{35}\text{S}$  reaction, it is the short ranged  $^{35}\text{S}$  which has a kinetic energy of 17 keV and triggers bubble. Lo and Apfel<sup>23</sup> have performed theoretical calculations and experimental measurements to study the neutron response functions for various types of SDDs,

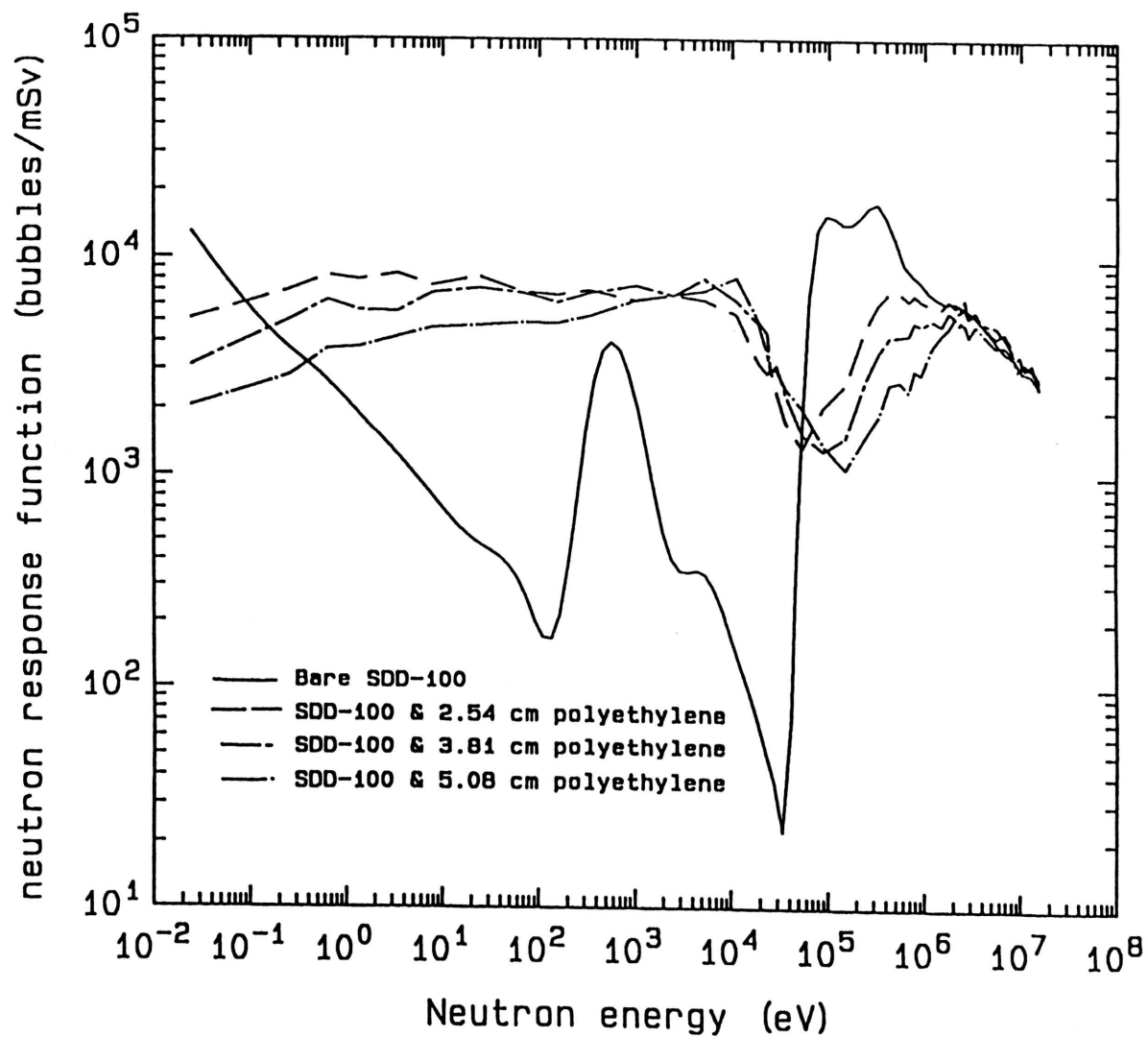


**Figure 4. The geometric configuration of a polyethylene-moderated SDD-100 dosimeter with incident neutrons in a plane parallel beam perpendicular to the axis of the detector. The neutron responses (in bubbles·cm<sup>2</sup>·n<sup>-1</sup>) of the dosimeter were calculated using Monte Carlo neutron transport code MORSE. Calculations were performed for a SDD-100 surrounded with various thicknesses (0, 2.54, 3.81, and 5.08 cm) of polyethylene.**

including SDD-100. Wang<sup>30</sup> used the Monte Carlo neutron transport code MORSE-CG<sup>27</sup> in conjunction with the BUGLE-80<sup>28</sup> cross section library to calculate the response function of a SDD-100 which is surrounded by polyethylene of various thicknesses. The geometric polyethylene-moderated SDD-100 by the Monte Carlo calculations is presented in Fig. 4. The calculational results (shown in Fig. 5), revealed that the bare SDD-100 favorably responds to thermal neutrons and neutrons with energies of several hundred keV, it does not respond as well to MeV neutrons, and it poorly responds to neutrons with energies of a few keV.

The idea of surrounding a SDD-100 with polyethylene was based on the fact that extra hydrogenous material might enhance the dosimeter's response to a few-keV neutrons while reducing its response to several-hundred-keV neutrons. Therefore, it makes the response function more dose equivalent. Indeed, the results from Monte Carlo calculation, as illustrated in Fig. 5, show that the additional polyethylene does make the SDD-100's response of neutrons more dose equivalent. The optimum thickness of polyethylene was determined to be 2.54 cm.





**Figure 5. The neutron response (in bubbles·mSv<sup>-1</sup>) for a SDD-100 dosimeter surrounded with various thicknesses of polyethylene as functions of neutron energy.**

### 3.0 Experimental Methods

This chapter provides the rationale, the detailed experimental setups, and the description of the experiment which were performed to verify the neutron response functions of a bare SDD-100 and a polyethylene-moderated SDD-100.

#### 3.1 Rationale

Ideally, one should use monoenergetic neutron sources at all energies to measure a detector's response function. In reality, monoenergetic neutrons rarely exist. An alternative way is to characterize the response function of a bare SDD-100 with a few specific energy ranges, and then choose a neutron source which emits neutrons in these energy ranges. According to Fig. 5 the neutron response function of a bare SDD-100 can be characterized with four specific neutron energy ranges: thermal, energies between 1 eV and 50 keV, energies between 70 keV and 700 keV, and energies above 1 MeV. In this study, we adopted four unique neutron sources which emits neutrons with energies roughly correspond to the four specific energy ranges. These four neutrons sources are:

1) A Pu-Be ( $\alpha,n$ ) sources which mainly emits several-MeV neutrons; 2) A D<sub>2</sub>O-moderated Cd-filtered <sup>252</sup>Cf spontaneous fission source which emits neutron with energies mainly between 1 eV and 500 keV; 3) the Al-filtered beam from the tangential beam port of the Kansas State University (KSU) TRIGA Mark II reactor. According to Noonam and Russell<sup>47</sup>, the Al-filtered beam should provide neutrons with energies preferentially around 20 keV and 4) the thermal neutrons produced in KSU TRIGA

reactor thermal column.

According to the calculated neutron response (shown in Fig. 4), one should expect to measure larger number of bubbles per  $\mu\text{Sv}$  with a bare SDD-100 using the  $\text{D}_2\text{O}$ -moderated  $^{252}\text{Cf}$  source or the thermal neutrons. Whereas, one should expect to measure smaller number of bubbles per  $\mu\text{Sv}$  with a bare SDD-100 using the Pu-Be source or the Al-filtered beam. The predicted bubble rates (in bubbles per  $\mu\text{Sv}$ ) for all four neutron sources are presented in section 3.3.

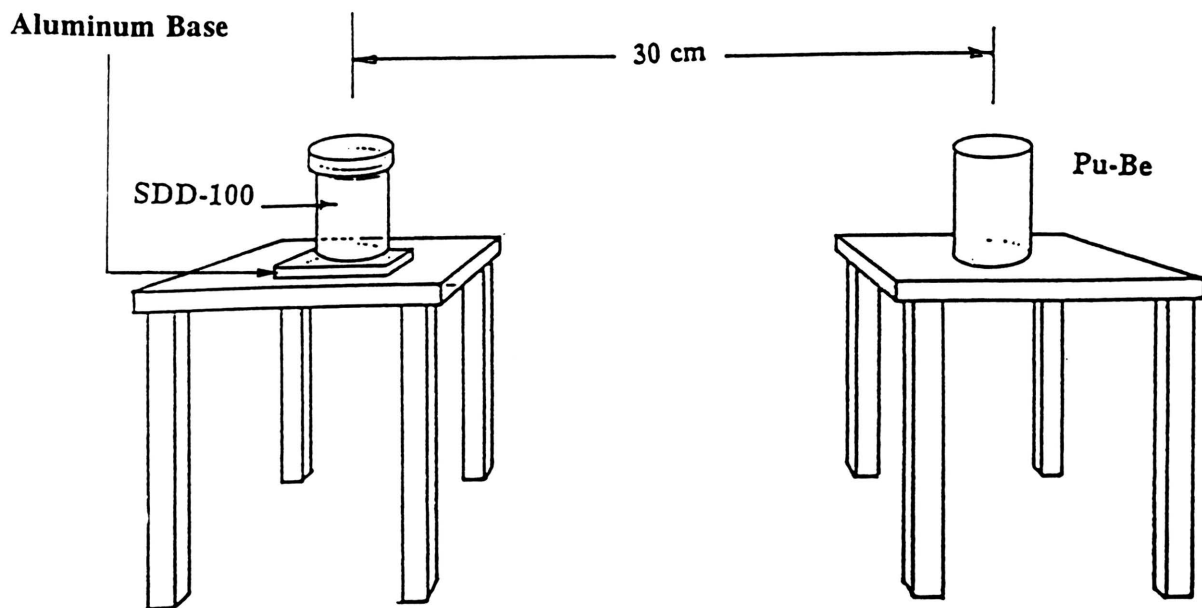
### 3.2 Description of Neutron Sources

The geometric configurations of the experiment with each neutron source are illustrated in figures 6 through 9 individually. The experiment with Pu-Be source was performed on the north side of the KSU TRIGA bay area and the experiment with  $\text{D}_2\text{O}$ -moderated  $^{252}\text{Cf}$  was performed on the south side of the KSU TRIGA bay area. The locations of these experiments were chosen due to their large open areas so that the room scattering effects were minimized.

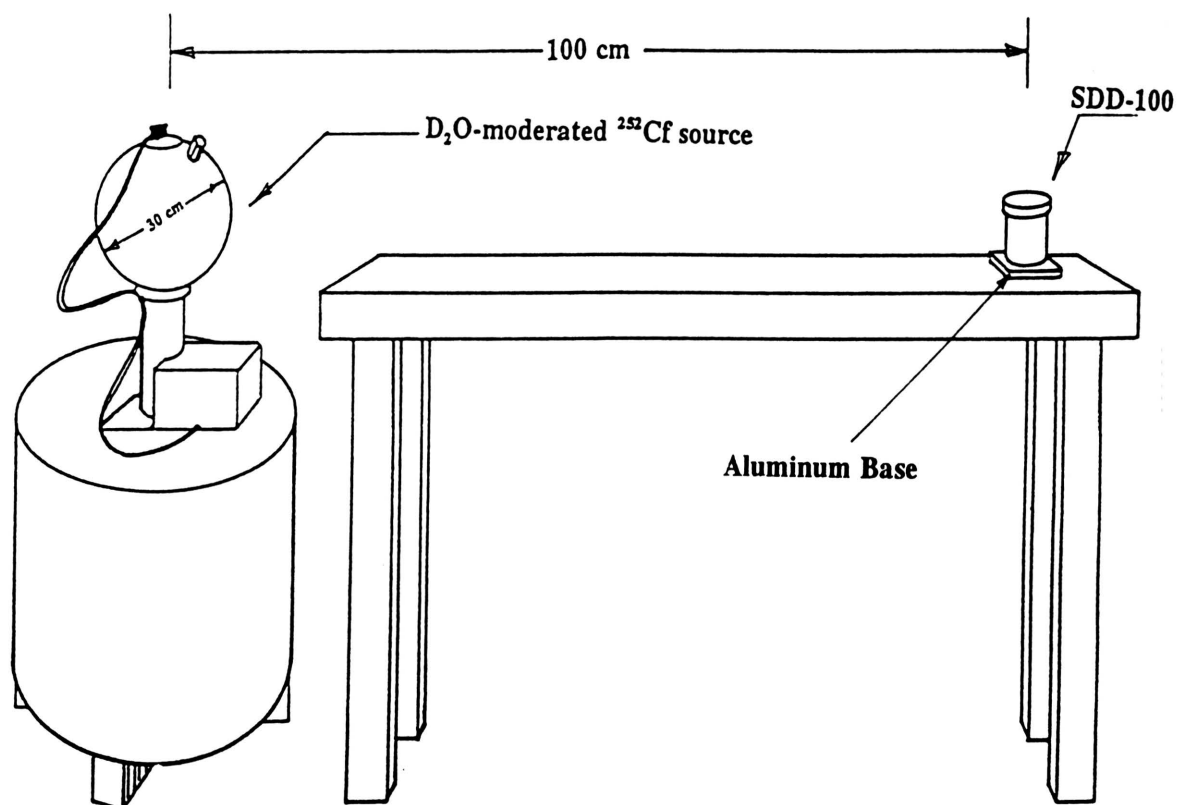
As it is shown in Fig. 6, SDD-100 dosimeter was placed at 30 cm from the Pu-Be source was so to keep the bubble rate reasonable. The reasonable bubble rates were judged to be between 200~500 bubbles per hour. Too high a bubble rate will expand and drive the gel-drop mixture out of the vial. Too low a bubble rate will make the counting time prohibitively long. Similarly, as shown in Fig. 7, the SDD-100 dosimeter was placed at 100 cm from the  $^{252}\text{Cf}$  source.

Fig. 8 shows the geometric configuration for the experiment using the Al-filtered

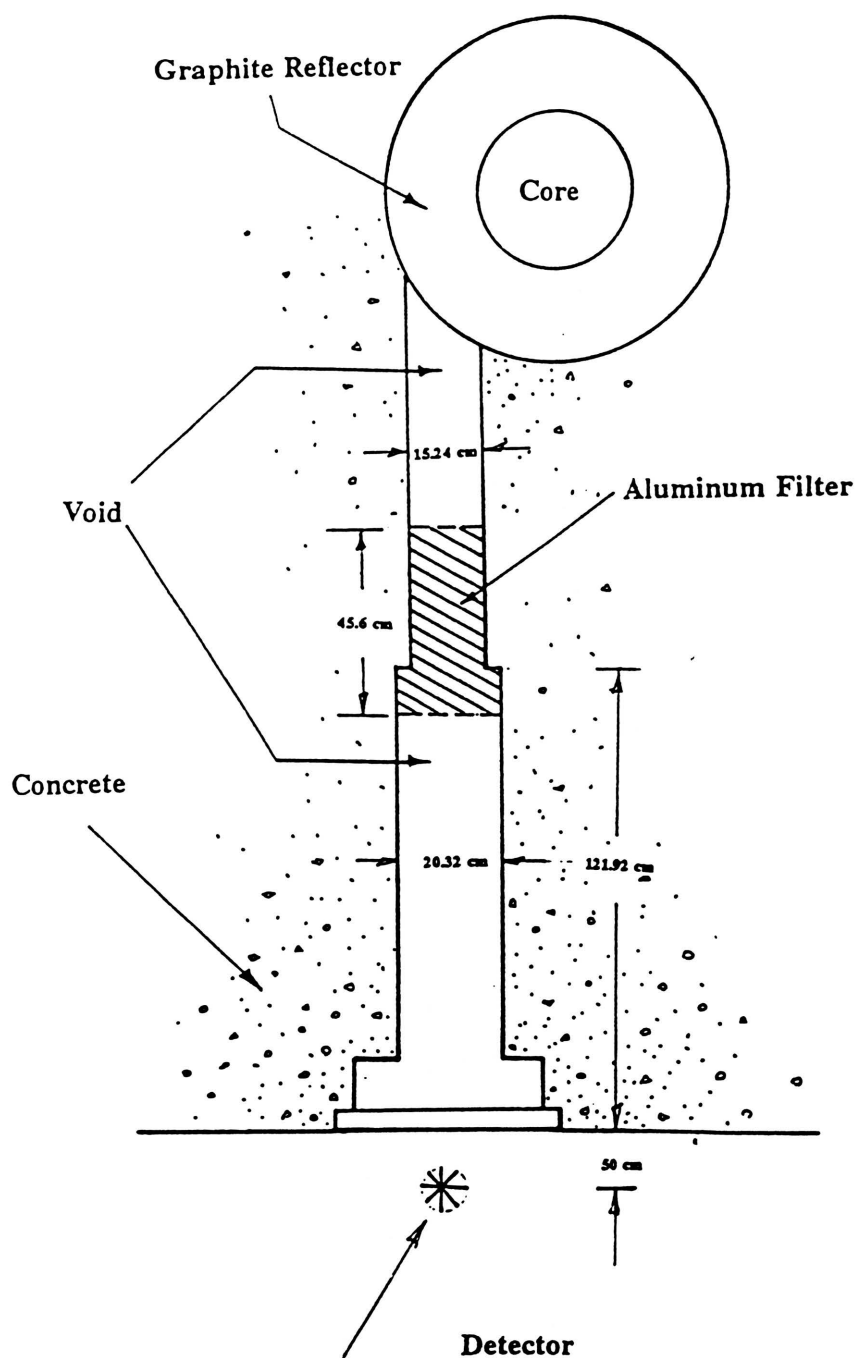
TRIGA tangential beam. The aluminum filter is 45.62 cm (18 inches) long. The SDD-100 was placed 50 cm off the concrete wall at the beam centerline. Fig. 9 shows the geometric configuration for the experiment using TRIGA thermal column. As it is shown, the SDD-100 was placed right outside the graphite block. For both experiments using TRIGA, the power levels used were 1 kW for the tangential beam experiment, 20 W for the thermal column beam experiment. The power levels were chosen so as to keep the bubble rates reasonable.



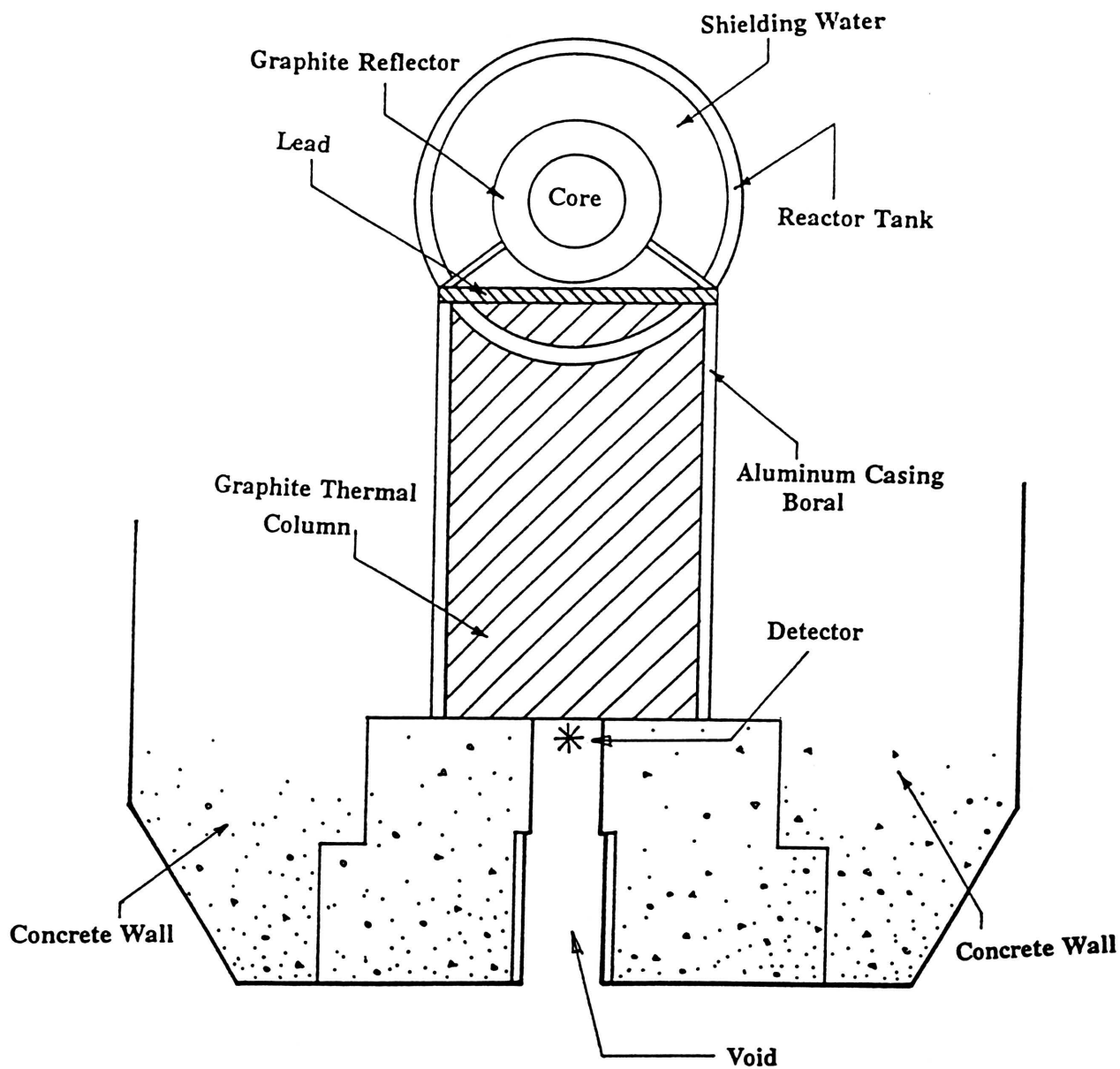
**Figure 6. The geometric configuration of the experiment with the Pu-Be source.**



**Figure 7.** The geometric configuration of the experiment with the  $D_2O$ -moderated  $^{252}Cf$  source.



**Figure 8. The geometric configuration of the experiment with the KSU TRIGA tangential beam.**



**Figure 9. The geometric configuration of the experiment with the KSU TRIGA thermal column.**



### 3.3 Theoretical Prediction of Bubbles

As part of the experimental design process, it was necessary first to theoretically predict the neutron responses (in bubbles· $\mu\text{Sv}^{-1}$ ) for a SDD-100 irradiated with the four sources, and to ensure that the bubble rates do vary significantly from one another. The neutron response (in bubbles· $\mu\text{Sv}^{-1}$ ) were calculated based on the following steps:

**Step 1:** The SDD's response, B (in bubbles), in a neutron field was given by:

$$B = \sum_i R_i \phi_i \quad (3.1)$$

Where:

$R_i$  (in bubbles· $\text{cm}^2 \cdot \text{n}^{-1}$ ) is the SDD's response to neutrons in energy group  $i$ ;

$\phi_i$  (in  $\text{n} \cdot \text{cm}^{-2}$ ) is the neutron fluence of the  $i^{\text{th}}$  energy group at the detector.

**Step 2:** The dose equivalent, H (in  $\mu\text{Sv}$ ), in a neutron field was given by

$$H = \sum_i F_i \phi_i \quad (3.2)$$

Where  $F_i$  (in  $\mu\text{Sv} \cdot \text{cm}^2 \cdot \text{n}^{-1}$ ) is the ICRP's neutron fluence-to-dose-equivalent (FTDE) conversion coefficient for neutrons in energy group  $i$ . There are many sets of FTDE conversion coefficients available<sup>42,41</sup>. In this thesis, we decided to use the set which converts neutrons fluence to deep dose equivalent index,  $H_{\text{Id}}$ , which is the maximum

value of dose equivalent that would occur (at a depth of 1 cm or more) in a 30 cm diameter of the International Commission on Radiation Unit (ICRU) tissue equivalent sphere<sup>41</sup>.  $H_{1,d}$  overestimates the whole-body effective dose equivalent, however, it is recommended to be used for radiation protection.

**Step 3:** The SDD's response,  $Q$  (in bubbles· $\mu\text{Sv}^{-1}$ ) were then obtained by

$$Q = \frac{B}{H} = \frac{\sum_i R_i \phi_i}{\sum_i F_i \phi_i} \quad (3.3)$$

In order to implement Equations 3.1 through 3.3, one has to have the detailed knowledge about the neutron fluence spectra,  $\phi_i$ , for with all four neutron sources.  $\phi_i$  at the SDD with Pu-Be source was obtained by

$$\phi_i = \frac{S_i}{4\pi r^2} \quad (3.4)$$

Where:

$S_i$  = the neutron source strength for energy group  $i$ ;

$r$  = the distance between the source and the SDD.

$S_i$  for Pu-Be is available from Stewart<sup>3</sup>, and  $r$  (distance from center of SDD to center of source) equals to 30 cm (as described in Fig. 6). Equation 3.4 ignores the scattering effect caused by air and room structure. Nevertheless, it should serve well for the experiment with Pu-Be source. Equation 3.4, however, does not work well for the  $\text{D}_2\text{O}$ -moderated  $^{252}\text{Cf}$  source because a neutron typically scatter many times in  $\text{D}_2\text{O}$  moderator before it reaches the SDD. To obtain  $\phi_i$  at the SDD-100 with  $\text{D}_2\text{O}$ -moderated

$^{252}\text{Cf}$  source, neutron transport calculation must be performed. In this thesis, we have used Monte Carlo transport code MORSE-CG<sup>27</sup>, in conjunction with the cross section library BUGLE-80<sup>28</sup> to calculate the  $\phi_i$  for the experiment with  $^{252}\text{Cf}$  source. Because of the symmetric geometry of the spherical system of the  $^{252}\text{Cf}$  source, neutron fluence spectrum at 100 cm from the source can be effectively estimated by so called "boundary crossing estimator (BCE)"<sup>27</sup>.  $S_i$  of  $^{252}\text{Cf}$  used in the MORSE calculation is available from Ing and Gross<sup>2</sup>. The user-written FORTRAN subroutines which define BCE and  $S_i$  are provided in Appendix A.

MORSE calculation, however, could not be performed accurately to obtain the  $\phi_i$  for the Al-filtered TRIGA beam, because the source (TRIGA core) is too far from the beam port. The  $\phi_i$  for the Al-filtered TRIGA beam was obtained from a set of Bonner Sphere (see photos in Appendix C1 and C2) measurements in conjunction with the SPUNIT<sup>36</sup> neutron spectrum unfolding code. The use of the KSU Bonner sphere system as a neutron spectrometer has been validated by Whitfill<sup>48</sup>. The neutron spectrum measured is shown in figures 11 through 13.

The absolute thermal neutron fluence in the TRIGA thermal column was determined by gold foil activation. It is appropriate to assume that the  $\phi_i$  in the TRIGA thermal column is pure thermal, because we observed very few bubbles for a relatively long period ( $\sim 1$  hr) with a Cd-covered SDD-100 in the TRIGA thermal column.

The bubble rates (in bubbles $\cdot\mu\text{Sv}^{-1}$ ) calculated using equation 3.1 through 3.3 and the  $\phi_i$  (obtained based in the aforementioned methods) are presented in Table 2 for both a bare SDD-100 and a SDD-100 surrounded with 2.54 cm (1 inch) of polyethylene.

As they are shown, calculations do predict high responses (in bubbles $\cdot\mu\text{Sv}^{-1}$ ) for

a bare SDD-100 irradiated with the D<sub>2</sub>O-moderated <sup>252</sup>Cf source and with thermal neutrons, and low response for a bare SDD-100 irradiated with Pu-Be source and with the Al-filtered TRIGA beam. Table 2 also the responses of the SDD-100 surrounded with 2.54 c of polyethylene for all four neutron sources are rather uniform. The calculated results in Table 2 ensures that the variation of responses (in bubbles·μSv<sup>-1</sup>) of a bare SDD-100 irradiated with the four neutron sources is indeed observable.

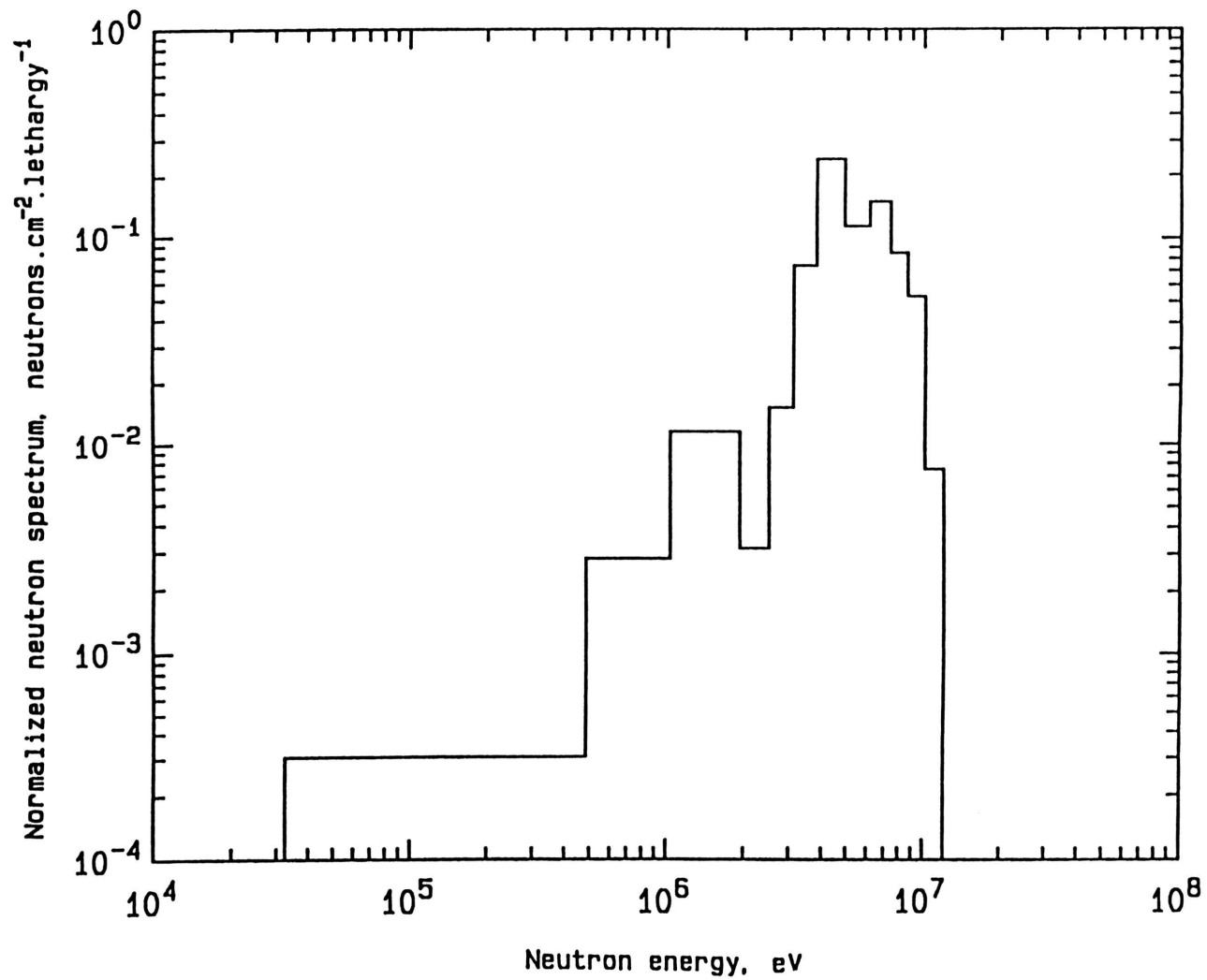


Figure 10. The normalized neutron fluence spectrum of a Pu-Be source.

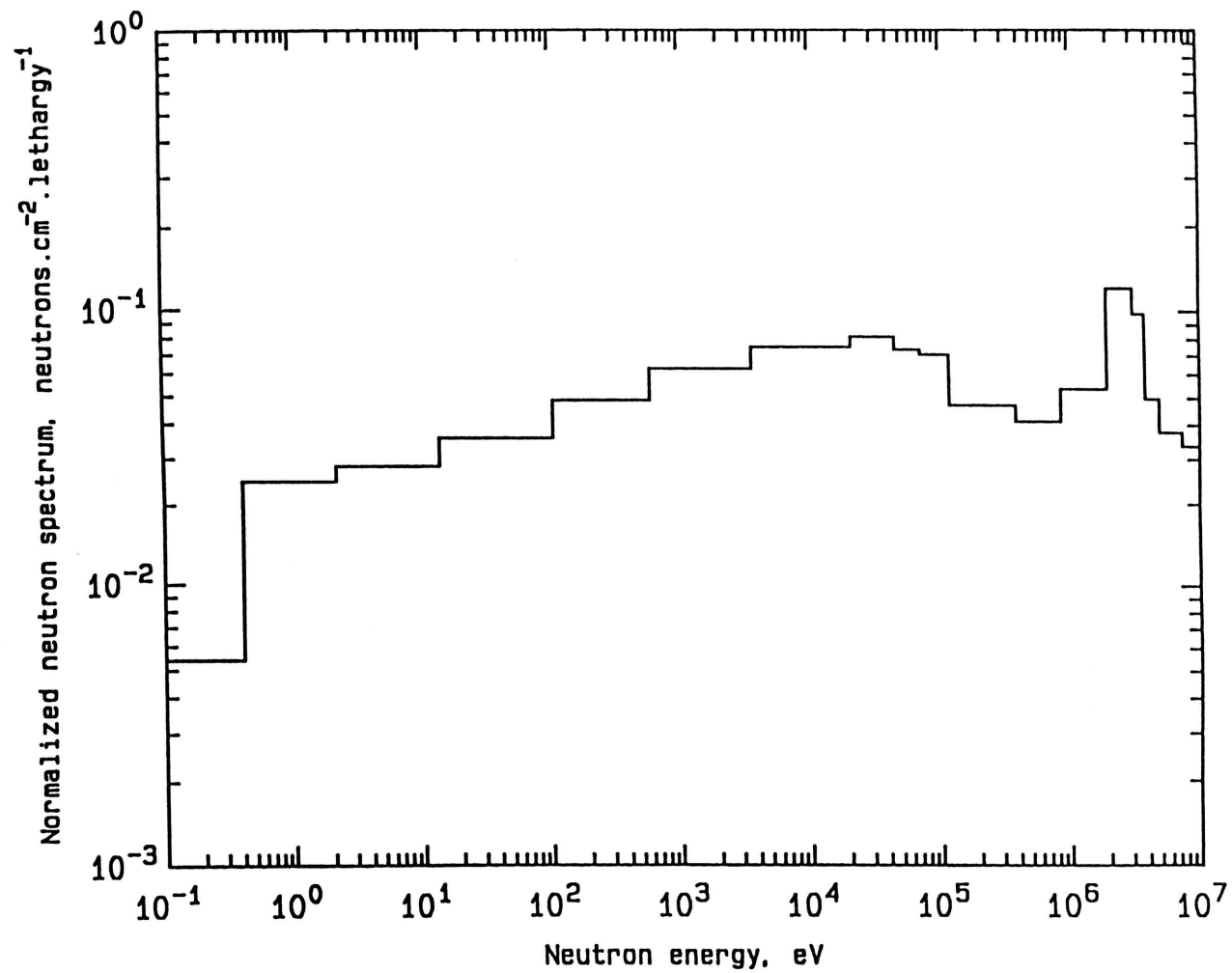


Figure 11. The normalized neutron fluence spectrum of a D<sub>2</sub>O-moderated <sup>252</sup>Cf source.

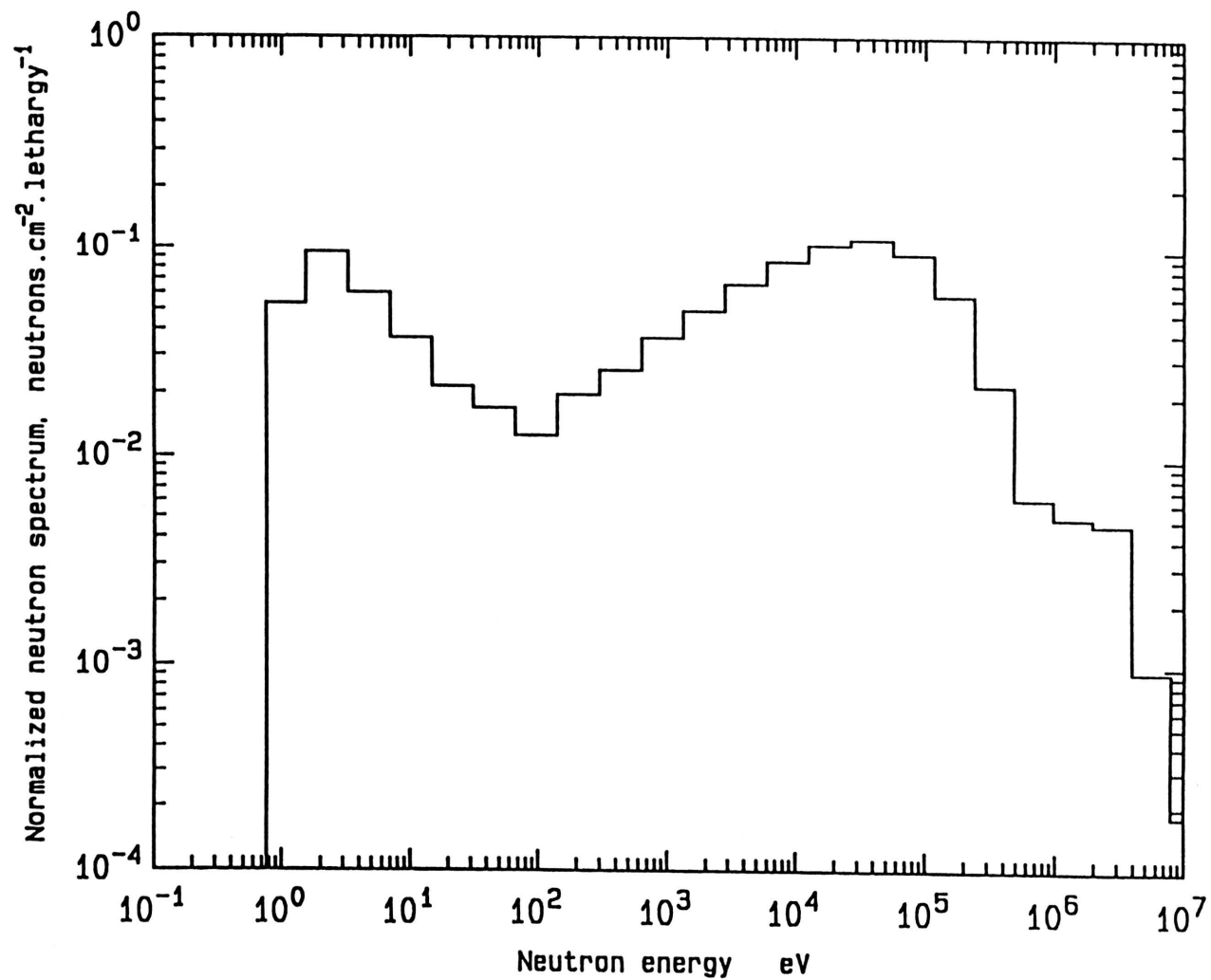


Figure 12. The normalized neutron fluence spectrum of the Al-filtered KSU TRIGA tangential beam.

**Table 2 The calculated neutron response for both a bare SDD-100 and a SDD-100 surrounded by 2.54 cm of polyethylene irradiated with various neutrons sources.**

Neutron Response (bubbles/ $\mu$ Sv)

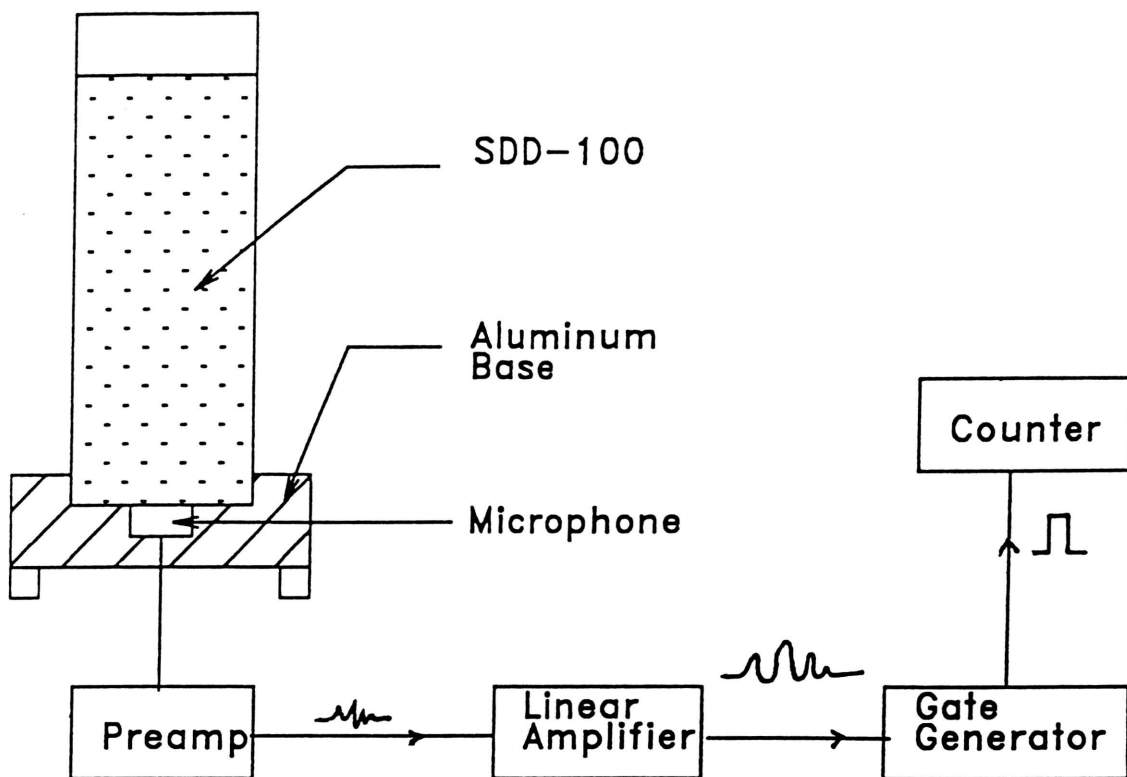
| Neutron Source                               | Bare SDD | SDD + 2.54 cm CH <sub>2</sub> |
|----------------------------------------------|----------|-------------------------------|
| Pu-Be                                        | 2.43     | 2.47                          |
| D <sub>2</sub> O-Moderated <sup>252</sup> Cf | 3.76     | 2.78                          |
| Al-Filtered TRIGA                            | 1.21     | 1.78                          |
| Tangential Beam                              |          |                               |
| Thermal Neutrons                             | 6.50     | 2.56                          |



### 3.4 The Measurement of Bubbles

In this experiment, we have developed our own system to count bubble events. The bubble counting system is shown as Fig. 13. Like most radiation detection systems, the bubble counting system consists of a SDD, a preamplifier, a linear amplifier, and a counter. But unlike them, the bubble counting system also includes an acoustic sensor which is in direct contact with the SDD vial so that the sound signal associated with a bubble event can be recorded and converted into a electric signal. The electric signal can then be processed by the preamplifier and the linear amplifier. The acoustic sensor used in this system is a Radio Shack mini microphone (Cat. No. 270-085). Also worth to mention in Fig. 7 and 8 is the aluminum base which is necessary to secure the positions of the SDD vial (see Appendix C, photo C4) and the mini microphone (see Fig. 13 and photo C3) so that good contact between them can be formed. In addition, the system also include a gate generator (EG&G GG200) which is connected between the linear amplifier and the counter and it is used to convert the sinusoidal sound signal associated with each bubble event to a single logic pulse. Without the gate generator (see Appendix C, photo C3), one bubble event may register several counts.

Since the bubble rate of a SDD-100 increases dramatically with temperatures between 10°C and 40°C<sup>43</sup>. The temperatures of the SDD-100 during the experiment were constantly monitored with a thermocouple (type K, NiCr-NiAl) (see Appendix C, photo C3). The variation of temperature is one of the major contributors to the overall uncertainty of the experimental results.



**Figure 13. The schematic description of the bubble counting system.**

## **4.0 Results and Discussion**

### **4.1 Introduction**

The experimental results are presented in this chapter. Comparisons between the calculational results (presented in chapter 3.0) and the experimental results are made, and the possible causes of discrepancies to are discussed. In addition, errors associated with the results are analyzed and the major contributors to the errors are discussed.

### **4.2 Experimental Results and Comparison with Calculation**

Table 3 shows the measured neutron response (in bubbles· $\mu\text{Sv}^{-1}$ ) for a SDD-100 irradiated with all four neutron fields.

Results are presented for both a bare SDD-100 and a SDD-100 surrounded with 2.54 cm of polyethylene. These bubble rates were obtained by dividing the total number of bubbles accumulated in each irradiation period with the corresponding accumulated dose equivalent (in  $\mu\text{Sv}$ ). The dose equivalent for each irradiation field was obtained using the methods discussed in chapter 3.0. In consistence with the calculational results, the measured neutron response of a bare SDD-100 irradiated with thermal neutrons or with a  $\text{D}_2\text{O}$ -moderated  $^{252}\text{Cf}$  source are significantly higher than those irradiated with a Pu-Be source or with the Al-filtered TRIGA beam. Also consistent is that the measured bubble rates for the polyethylene-moderated SDD-100 irradiated with all four neutron fields are relatively uniform. This consistency between calculations and measurements

**Table 3 The measured neutron responses for both a bare SDD-100 and a SDD-100 surrounded by 2.54 cm polyethylene irradiated with various neutron sources.**

Neutron Response (bubbles· $\mu$ Sv<sup>-1</sup>)

| Neutron Source                               | Bare SDD         | SDD + 2.54 cm<br>Polyethylene |
|----------------------------------------------|------------------|-------------------------------|
| Pu-Be                                        | $1.86 \pm 6.4\%$ | $1.55 \pm 5.9\%$              |
| D <sub>2</sub> O-Moderated <sup>252</sup> Cf | $2.61 \pm 7.6\%$ | $1.83 \pm 7.6\%$              |
| Al-Filtered TRIGA<br>Tangential Beam         | $1.41 \pm 6.4\%$ | $1.45 \pm 6.3\%$              |
| Thermal Neutrons                             | $2.80 \pm 6.3\%$ | $1.84 \pm 7.6\%$              |

confirms that the polyethylene-moderated SDD-100 dosimeter is indeed more dose-equivalent in a free neutron field than is a bare SDD-100 dosimeter. Overall speaking, however, the absolute values of the bubble rates predicted by calculations are higher than the measured values. This discrepancy is most likely due to the uncertainty about the quantity of Freon-12 in the SDD-100, because the neutron response of a SDD-100 is directly proportional to the quantity of the neutron-sensitive material (the Freon-12). The other discrepancy is that the calculation seems to overestimate the response for a bare SDD-100 irradiated with thermal neutrons. This overestimation was also reported by others<sup>23</sup>. One possible explanation is provided below. A value of 400 mbarns was used in the calculation as the cross section of  $^{35}\text{Cl}(n,p)^{35}\text{S}$  for thermal neutrons. This value of 400 mbarns corresponds to the cross section for the neutrons with energy of 0.0253 eV<sup>23</sup>. Because the average energy of thermal neutrons with a reactor thermal column may be higher than 0.0253 eV, and because the cross section of  $^{35}\text{Cl}(n,p)^{35}\text{S}$  follows the  $E^{-1/2}$  relationship, the average cross section of  $^{35}\text{Cl}(n,p)^{35}\text{S}$  for reactor thermal neutrons may be significantly lower than 400 mbarns. This argument can also be presented by

$$\overline{\sigma}_{\text{th}} = \frac{\int_0^{0.4 \text{ eV}} \sigma(E_n) \phi_{\text{th}}(E_n) dE_n}{\int_0^{0.4 \text{ eV}} \phi_{\text{th}}(E_n) dE_n} = \frac{\int_0^{0.4 \text{ eV}} \frac{K \sigma_0}{\sqrt{E_n}} \phi_{\text{th}}(E_n) dE_n}{\int_0^{0.4 \text{ eV}} \phi_{\text{th}}(E_n) dE_n} \quad (4.1)$$

Where  $\overline{\sigma}_{\text{th}}$  is the average cross section for thermal neutrons,  $\phi_{\text{th}}(E_n)$  is the thermal neutron distribution as a function of neutron energy ( $E_n$ ),  $K$  is a constant, and  $\sigma_0$  is the cross section for  $E_n$  at 0.0253 eV (which is 400 mbarns in this case). For thermal

neutron population with the Maxwellian distribution<sup>50</sup> at 25 °C, equation 4.1 gives

$$\overline{\sigma_{th}} = \frac{\sqrt{\pi}}{2} \sigma_o = 354.5 \text{ mbarns} \quad (4.2)$$

The value of  $\overline{\sigma_{th}}$  cross section may be much lower if the actual  $\phi_{th}(E_n)$  is significantly harder than the Maxwellian Distribution. Since the bubble rate for thermal neutrons is directly proportional to the cross section of  $^{35}\text{Cl}(n,p)^{35}\text{S}$  reaction, the use of 400 mbarns tends to overestimate the response.

### 4.3 Error Analysis

There are three major contributors to the overall errors of the experimental results, namely: 1) the uncertainty about the number of droplets in an unused SDD-100. The number of droplets of an unused SDD-100 is known to be between 30000 and 40000<sup>43</sup>. It affects the overall results because the measured bubble rates (as shown in table 3) must take account of the droplet depletion effect which is a function of the number of droplets in the unused SDD-100. 2) The variation of temperature during the experiment. It was reported<sup>43</sup> that the response of SDD-100 to  $^{252}\text{Cf}$  neutron source increases by ~5% per °C from 10°C to 32 °C. The increase of response of a SDD-100 is due to the decrease of threshold energy ( $E_{min}$ , in equation 2.6) for increased temperature. 3) The Poisson statistics directly associated with the bubble events.

To perform error analysis for the results shown in table 3, the bubble rates,  $U$ , is represented as

$$U = X \cdot Y \cdot Z \quad (4.3)$$

Where X is the actual measured counts of bubble event, Y is the correction factor which takes account of the droplet depletion effect. In this analysis 35000 was chosen to be the number of droplets of an unused SDD-100. Therefore,

$$Y = \frac{35000}{35000 - \xi} \quad (4.4)$$

where  $\xi$  is the total number of droplets which had been depleted in a SDD-100. Z is the correction factor which take account of the effect due to temperature variation. For the first three experiments listed in Table 3

$$Z = 1 + 0.05 (T - \bar{T}) \quad (4.5)$$

where T is the actual temperature of the SDD-100 during a experiment, and  $\bar{T}$  is the average temperature of the SDD-100 for these three experiments. In the experiment with thermal neutrons, bubbles triggered by  $^{35}\text{Cl}(n,p)^{35}\text{S}$  reaction which has a fixed Q-value, and therefore, the bubble rate should not be affected by the change of the temperature (or the threshold energy  $E_{\min}$ ). That is, the correction factor due to temperature (Z) equals to 1 for the thermal neutron experiment. The error associated with U (X,Y,Z,.....) is given by<sup>46</sup>

$$\sigma_U^2 = \left(\frac{\partial U}{\partial X}\right)^2 \sigma_X^2 + \left(\frac{\partial U}{\partial Y}\right)^2 \sigma_Y^2 + \left(\frac{\partial U}{\partial Z}\right)^2 \sigma_Z^2 + \dots \quad (4.6)$$

From Equation 4.3, one finds

$$\frac{\partial U}{\partial X} = Y \cdot Z, \quad \frac{\partial U}{\partial Y} = X \cdot Z, \quad \text{and} \quad \frac{\partial U}{\partial Z} = X \cdot Y \quad (4.7)$$

Substitute Equation 4.7 into Equation 4.6, one obtains

$$\sigma_U^2 = Y^2 Z^2 \sigma_X^2 + X^2 Z^2 \sigma_Y^2 + X^2 Y^2 \sigma_Z^2 \quad (4.8)$$

By dividing both sides of Equation 4.8 by the square of Equation 4.3, it becomes

$$\left(\frac{\sigma_U}{U}\right)^2 = \left(\frac{\sigma_X}{X}\right)^2 + \left(\frac{\sigma_Y}{Y}\right)^2 + \left(\frac{\sigma_Z}{Z}\right)^2 \quad (4.9)$$

$\frac{\sigma_U}{U}$  is the fractional error associated with U.  $\sigma_X$  was determined by the standard deviation of the total number of bubble events recorded in an experiment. By assuming that bubble event follows Poisson distribution, one has

$$\sigma_X = \sqrt{X} \quad (4.10)$$

and

$$\frac{\sigma_X}{X} = \frac{1}{\sqrt{X}} \quad (4.11)$$

The typical values of X of our experiments are between 200 and 500. Therefore  $\frac{\sigma_X}{X}$  typically varies between 0.045 and 0.071.

$\sigma_Y$  was obtained by introducing the two extreme cases into Equation 4.3. That is,

$$Y = 1 \pm \sigma_Y \quad (4.12)$$

$$Y_L = 1 - \sigma_Y^L = \frac{40000}{40000 - \xi} \quad (4.13)$$

and



$$Y_H = 1 + \sigma_Y^H = \frac{30000}{30000-\xi} \quad (4.14)$$

Thus,

$$\sigma_Y^L = \frac{35000}{35000-\xi} - \frac{40000}{40000-\xi} \quad (4.15)$$

or

$$\sigma_Y^H = \frac{30000}{30000-\xi} - \frac{35000}{35000-\xi} \quad (4.16)$$

It can be shown that  $\sigma_Y^H$  is always greater than  $\sigma_Y^L$ , we decided to use  $\sigma_Y^H$  as  $\sigma_Y$ . In our experiment, the values of  $\xi$  are between 0 and 3000. Thus,  $\sigma_Y$  or  $(\sigma_Y/Y)$  typically varies from 0 to 0.0174 (using Equation 4.16).

As indicated in Section 3.4, the temperature variation among experiments were  $23.5 \pm 1^\circ\text{C}$ . That is,

$$\bar{T} = 22.5^\circ\text{C} \text{ and } T - \bar{T} = 1^\circ\text{C}$$

One can then rewrite Equation 4.5 as

$$Z = 1 \pm 0.05 \quad (4.17)$$

or

$$\sigma_Z = \frac{\sigma_Z}{Z} = 0.05 \quad (4.18)$$

In summary, the error reported in Table 3 were obtained by applying Equations 4.9, 4.11, 4.16, and 4.18 to each experiment. One may also conclude that the major contributors to the experimental errors are the error directly associated with the counting statistics and the error associated with the temperature variations among experiments.

## **5.0 Conclusions and Remarks**

### **5.1 Conclusions**

In this study, we have experimentally investigated the neutron response functions of a bare SDD-100 dosimeter, and a SDD-100 dosimeter surrounded with 2.54 cm of polyethylene. The experimental results is very much consistent with the calculational results, and the following conclusions can be drawn:

- 1) The neutron responses (in bubbles· $\mu\text{Sv}^{-1}$ ) for a bare SDD-100 in a free neutron field are high for thermal neutrons and neutrons with energies between 100 and 500 keV, and significantly lower for MeV neutrons and lowest for neutrons with energies between 1 and 50 keV.
- 2) The neutron responses (in bubbles· $\mu\text{Sv}^{-1}$ ) for a SDD-100 surrounded with 2.54 cm of polyethylene is quite uniform for neutrons with all energies between thermal and 10 MeV. In other words, this "polyethylene-moderated" SDD-100 is a good dose-equivalent dosimeter.

### **5.2 Remarks**

There are several remarks need to be made:

- 1) The variation of SDD's response with temperature has been known as the major disadvantage. With the concept of a moderated SDD, one may use circulating water (instead of solid polyethylene) as the neutron moderator of which the

temperature can be accurately maintained with a small heater.

The droplet depletion effect may be overcome with an automatic compression system. In this system, the SDD is housed in a pressure chamber which is connected to a bottle of compressed gas (e.g. N<sub>2</sub>, He, or air) via a valve. As soon as a bubble event is recorded, the logic pulse is sent to open the valve of gas bottle and compress the bubble back to the liquid droplet. Such a system, however, will introduce a dead time period to the SDD after each event, because the SDD is insensitive to neutrons when it is under pressure.

Due to the disagreement between calculations and measurements for the SDD's response to thermal neutrons, it is worthwhile to repeat the experiment using a monoenergetic thermal neutron beam so that the cross section of  $^{35}\text{Cl}(n,p)^{35}\text{S}$  reaction is well defined.

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## **Appendix A**

A FORTRAN program which provides the neutron source spectrum of  $^{252}\text{Cf}$  and the boundary crossing estimator, and was used with MORSE Code to calculate the neutron spectrum at various distances from a  $\text{D}_2\text{O}$ -moderated  $^{252}\text{Cf}$  source.

```

C ** THIS IS THE MAIN ROUTINE FOR A Cf-252 SOURCE * * * * *
C **
      COMMON NC(170000)
C ** (REGION SIZE NEEDED IS ABOUT 150K + 4*(SIZE OF BLANK COMMON IN WORDS) ) *
C ** NOTE - THE ORDER OF COMMONS IN HTIS ROUTINE IS IMPORTANT AND MUST CORRES-
C ** POND TO THE ORDER USED IN DUMP ROUTINES SUCH AS HELP, XSCHLP, AND USRHLP
C **
C ** LABELLED COMMONS FOR WALK ROUTINES * * * * *
      COMMON /APOLLO/ AGSTRT, DDF, DEADWT(26), ITOUT, ITIN
      COMMON /FISBNK/ MFISTP
      COMMON /NUTRON/ NAME
C **
C ** LABELLED COMMONS FOR CROSS-SECTION ROUTINES * * * * *
      COMMON /LOCSIG/ ISCCOG
      COMMON /MEANS/ NM
      COMMON /MOMENT/ NMCM
      COMMON /QAL/ Q
      COMMON /RESULT/ POINT
C **
C ** LABELLED COMMONS FOR USER ROUTINES * * * * *
      COMMON /GEOMC/ XTWO
      COMMON /NORMAL/ UNORM
C **
C ** COMMON /DUMMY/ WILL NOT BE FOUND ELSEWHERE IN THE PROGRAM * * * * *
      COMMON /DUMMY/ DUM
C **
      DATA JUNK /Z48484848/
      NLFT = (LOC(DUM) - LOC(NC(1)))/4
      DO 10 I=1,NLFT
10      NC(I) = JUNK
      ITOUT = 6
      ITIN = 5
      NLFT = (LOC(AGSTRT) - LOC(NC(1)))/4
      CALL MORSE(NLFT)
      STOP
      END
C **
      SUBROUTINE BANKR(NBNKID)
C DO NOT CALL EUCLID FROM BANKR(7)
      COMMON /APOLLO/ AGSTRT,DDF,DEADWT(5),ETA,ETATH,ETAUSD,UINP,VINP,
1 WINP,WTSTRT,XSTRT,YSTRT,ZSTRT,TCUT,XTRA(10),
2 I0,I1,MEDIA,IADJM,ISBIAS,ISOUR,ITERS,ITIME,ITSTR,LOCWTS,LOCFWL,
3 LOCEPR,LOCNSC,LOCFSN,MAXGP,MAXTIM,MEDALB,MGPREG,MXREG,NALB,
4 NDEAD(5),NEWNM,NGEOM,NGPQT1,NGPQT2,NGPQT3,NGPQTG,NGPQTN,NITS,
5 NKCALC,NKILL,NLAST,NMEM,NMGP,NMOST,NMTG,NOLEAK,NORMF,NPAST,
6 NPSC(13),NQUIT,NSIGL,NSOUR,NSPLT,NSTRT,NXTRA(10)
      COMMON /NUTRON/NAME,NAMEX,IG,IGO,NMED,MEDOLD,NREG,U,V,W,UOLD,VOLD,
1 WOLD,X,Y,Z,XOLD,YOLD,ZOLD,WATE,OLDWT,WTBC,BLZNT,BLZON,AGE,OLDAGE
      NBNK = NBNKID
      IF (NBNK) 100,100,140
100      NBNK = NBNK + 5
      GO TO (104,103,102,101), NBNK
101      CALL STRUN
C      CALL HELP(4HSTRU,1,1,1,1)
      RETURN
102      NBAT= = NITS - ITERS

```

```

      NSAVE = NMEM
      CALL STBTCH(NBAT)
C ** NBAT IS THE BATCH NO. LESS ONE
      RETURN
103   CALL NBATCH(NSAVE)
C ** NSAVE IS THE NO. OF PARTICLES STARTRED IN THE LAST BATCH
      RETURN
104   CALL NRUN(NITS,NQUIT)
C ** NITS IS THE NO. OF BATCHES COMPLETED IN THE RUN JUST COMPLETED
C ** NQUIT .GT. 1 IF MORE RUNS REMAIN
C **      .EQ. 1 IF THE LAST SCHEDULED RUN HAS BEEN COMPLETED
C **      IS THE NEGATIVE NO. OF COMPLETE RUNS, WHEN AN EXECUTION TIME
C **      KILL OCCURS
      RETURN
140   GO TO (1,2,3,4,5,6,7,8,9,10,11,12,13), NBNK
C **
C NBNKID COLL TYPE BANKR CALL      NBNKID COLL TYPE BANKR CALL
C 1      SOURCE      YES (MSOUR)    2      SPLIT        NO  (TESTW)
C 3      FISSION      YES (FPROB)    4      GAMGEN        YES (GSTORE)
C 5      REAL COLL    YES (MORSE)    6      ALBEDO        YES (MORSE)
C 7      BDRYX        YES (NXTCOL)   8      ESCAPE        YES (NXTCOL)
C 9      E-CUT        NO  (MORSE)   10     TIMEKILL       NO  (MORSE)
C 11     R R KILL     NO  (TESTW)    12     R R SURV       NO  (TESTW)
C 13     GAMLOST     NO  (GSTORE)
C **
1     RETURN
2     RETURN
3     RETURN
4     RETURN
5     RETURN
6     RETURN
7     CALL BDRYX
8     RETURN
9     RETURN
10    RETURN
11    RETURN
12    RETURN
13    RETURN
      END
C **
      SUBROUTINE BDRYX
C
C ** CHECK AND SCORE IF DETECTOR IS REACHED
C
      COMMON /LOCSIG/ ISTART,ISCOG,INABOG,IGABOG,IFPRG,IFNGP,IFSPOG,
1 IDSGOG,IPRBNG,IPRBGG,ISCANG,ISCAGG,ISPORG,ISPORT,INPBUF,ISIGOG,
2 INFPOG,IABSOG,ITISG,NGP,NDS,NGG,NDSG,INGP,INDS,NMEDD,NELEM,NMIX,
3 NCOEF,NSCT,NTS,NTG,NSDNGP,NSDNNG,IADJ,NME,LOC,INGS,INSG,I1,I0,KKK,
4 IXTAPE,IDEL,ITEML,ITEMG,IRSG,IRGSG,ISTR,IPRIN,IFMU,IMOM,IDTF,
5 ISTAT,IPUN,NUS,NGN,IHT,INUS,INUSN,INGN,INGNP,INNN,IGGG
      COMMON /NUTRON/NAME,NAMEX,IG,IGO,NMED,MEDOLD,NREG,U,V,W,UOLD,VOLD,
1 WOLD,X,Y,Z,XOLD,YOLD,ZOLD,WATE,OLDWT,WTBC,BLZNT,BLZON,AGE,OLDAGE
      COMMON /POET/ ND,NNE,NE,NT,NA,NRESP,NEX,NEXND,NDNR,NTNR,NTNE,
1 NAN,NTNDNR,NTNENC,NANEND,LOCSP,LOCXD,LOCIB,LOCCO,LOCT,LOCUD,
2 LCCSD,LOCQE,LOCQT,LOCQTE,LOCQAE,LMAX,EFIRST,EGTOP
      COMMON BC(1)

```

```

        DIMENSION NC(1),RR(15)
        EQUIVALENCE (BC(1),NC(1))
        DATA (RR(I),I=1,5)/18.3,50.0,100.0,200.0,400.0
        R=SQRT(X**2+Y**2+Z**2)
C      C * *
C      C * * CHECK WHICH BDY THE PARTICLE IS CROSSING AND SCORE IT
C      C * *
        DO I=1,5
        CHECK=ABS(R-RR(I))
10      10 IF(CHECK.KT.0.001) GOTO 20
        RETURN
20      20 AREA=4.*3.141592654**2
        COS=(X*U+Y(V+Z*W)/R
        CON=(WATE/AREA)/ABS(COS)
        GO TO 99
C      C * *
99      99 CALL FLUXST(I,IG,CON,0.0,0.0,0)
        RETURN
        END
C      C * *
        SUBROUTINE SOURCE(IG,U,V,W,X,Y,Z,WATE,AG)
        COMMON /PDET/ ND,NNE,NE,NT,NA,NRESP,NEX,NEXND,NEND,NDNR,NTNR,NTNE,
1 NANEN,NTNDNR,NTNEND,NANEND,LOCRSP,LOCXD,LOCIB,LOCCO,LOCT,LOCUD,
2 LOCSD,LOCQE,LOCQT,LOCQTE,LOCQAE,LMAX,EFIRST,EGTOP
        COMMON BC(1)
        DIMENSION NC(1)
        EQUIVALENCE (BC(1),NC(1))
        X=0.
        Y=0.
        Z=0.
        RAND=FLTRNF(0)
        IF(RAND.LT.0.0018) GO TO 10
        IF(RAND.GT.0.0018.AND.RAND.LT.0.0036) GO TO 20
        IF(RAND.GT.0.0036.AND.RAND.LT.0.01756) GO TO 30
        IF(RAND.GT.0.01756.AND.RAND.LT.0.03153) GO TO 40
        IF(RAND.GT.0.03153.AND.RAND.LT.0.04933) GO TO 50
        IF(RAND.GT.0.04933.AND.RAND.LT.0.06714) GO TO 60
        IF(RAND.GT.0.06714.AND.RAND.LT.0.12192) GO TO 70
        IF(RAND.GT.0.12192.AND.RAND.LT.0.28192) GO TO 80
        IF(RAND.GT.0.28192.AND.RAND.LT.0.31351) GO TO 90
        IF(RAND.GT.0.31351.AND.RAND.LT.0.3451) GO TO 100
        IF(RAND.GT.0.3451.AND.RAND.LT.0.3767) GO TO 110
        IF(RAND.GT.0.3767.AND.RAND.LT.0.40829) GO TO 120
        IF(RAND.GT.0.40829.AND.RAND.LT.0.43989) GO TO 130
        IF(RAND.GT.0.43989.AND.RAND.LT.0.47148) GO TO 140
        IF(RAND.GT.0.47148.AND.RAND.LT.0.54735) GO TO 150
        IF(RAND.GT.0.54735.AND.RAND.LT.0.62322) GO TO 160
        IF(RAND.GT.0.62322.AND.RAND.LT.0.69909) GO TO 170
        IF(RAND.GT.0.69909.AND.RAND.LT.0.77496) GO TO 180
        IF(RAND.GT.0.77496.AND.RAND.LT.0.81148) GO TO 190
        IF(RAND.GT.0.81148.AND.RAND.LT.0.848) GO TO 200
        IF(RAND.GT.0.848.AND.RAND.LT.0.88453) GO TO 210
        IF(RAND.GT.0.88453.AND.RAND.LT.0.92105) GO TO 220
        IF(RAND.GT.0.92105.AND.RAND.LT.0.94366) GO TO 230
        IF(RAND.GT.0.94366.AND.RAND.LT.0.96627) GO TO 240
        IF(RAND.GT.0.96627.AND.RAND.LT.0.98888) GO TO 250

```

```

IF(RAND.GT.0.98888.AND.RAND.LT.0.99484) GO TO 260
IF(RAND.GT.0.99484.AND.RAND.LT.1.0) GO TO 270
10  IG=2
    GO TO 300
20  IG=3
    GO TO 300
30  IG=4
    GO TO 300
40  IG=5
    GO TO 300
50  IG=6
    GO TO 300
60  IG=7
    GO TO 300
70  IG=8
    GO TO 300
80  IG=9
    GO TO 300
90  IG=10
    GO TO 300
100 IG=11
    GO TO 300
110 IG=12
    GO TO 300
120 IG=13
    GO TO 300
130 IG=14
    GO TO 300
140 IG=15
    GO TO 300
150 IG=16
    GO TO 300
160 IG=17
    GO TO 300
170 IG=18
    GO TO 300
180 IG=19
    GO TO 300
190 IG=20
    GO TO 300
200 IG=21
    GO TO 300
210 IG=22
    GO TO 300
220 IG=23
    GO TO 300
230 IG=24
    GO TO 300
240 IG=25
    GO TO 300
250 IG=26
    GO TO 300
260 IG=28
    GO TO 300
270 IG=32
300 WATE=1.0

```

```
CALL GTISO(U,V,W)
AG=0.0
RETURN
END
END
```

## **Appendix B**

Input file of MORSE Code, which was used to calculate the neutron spectrum at various distances from a D<sub>2</sub>O-moderated <sup>252</sup>Cf-source.

# **Input Data for MORSE Code**

D2O MODERATED, CF252 SOURCE, AT 18.3, 50, 100, 200, AND 400 CM

|      |      |     |     |           |          |           |           |           |   |     |   |   |
|------|------|-----|-----|-----------|----------|-----------|-----------|-----------|---|-----|---|---|
| 5000 | 5500 | 10  | 1   | 67        | 0        | 67        | 67        | 0         | 0 | 999 | 4 | 0 |
| 0    | 0    | 0   | 0   | 1.0000E+0 | 1.000E-5 | 1.0000E+4 | 1.0000E+0 | 2.2000E+5 |   |     |   |   |
|      | 0.0  | 0.0 | 0.0 | 0.0       | 0.0      | 0.0       | 0.0       |           |   |     |   |   |

|           |           |           |           |           |           |           |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1.7333E+7 | 1.4191E+7 | 1.2214E+7 | 1.0000E+7 | 8.6071E+6 | 7.4682E+6 | 6.0653E+6 |
| 4.9656E+6 | 3.6788E+6 | 3.0119E+6 | 2.7253E+6 | 2.4660E+6 | 2.3653E+6 | 2.3457E+6 |
| 2.2313E+6 | 1.9205E+6 | 1.6530E+6 | 1.3534E+6 | 1.0026E+6 | 8.2085E+5 | 7.4274E+5 |
| 6.0810E+5 | 4.6787E+5 | 3.6883E+5 | 2.9720E+5 | 1.8316E+5 | 1.1109E+5 | 6.7379E+4 |
| 4.0868E+4 | 3.1828E+4 | 2.6058E+4 | 2.4176E+4 | 2.1875E+4 | 1.5034E+4 | 7.1017E+3 |
| 3.3546E+3 | 1.5846E+3 | 4.5400E+2 | 2.1445E+2 | 1.0130E+2 | 3.7267E+1 | 1.0677E+1 |
| 5.0435E+0 | 1.8554E+0 | 7.7642E-1 | 4.1399E-1 | 1.0000E-1 | 1.4000E+7 | 1.0000E+7 |
| 8.0000E+6 | 7.0000E+6 | 6.0000E+6 | 5.0000E+6 | 4.0000E+6 | 3.0000E+6 | 2.0000E+6 |
| 1.5000E+6 | 1.0000E+6 | 8.0000E+5 | 7.0000E+5 | 6.0000E+5 | 4.0000E+5 | 2.0000E+5 |
| 1.0000E+5 | 6.0000E+4 | 3.0000E+4 | 2.0000E+4 |           |           |           |

91E0B6D3B362

|    |   |   |   |   |   |        |        |        |        |  |
|----|---|---|---|---|---|--------|--------|--------|--------|--|
| 1  | 1 | 1 | 0 | 0 | 1 | 67     |        |        |        |  |
| 0  | 0 | 0 | 1 | 1 | 1 | 1.0E+1 | 1.0E-2 | 1.02+0 | 5.0E-1 |  |
| -1 |   |   |   |   |   |        |        |        |        |  |

0 0 0 0

0 0 COMBINATORIAL GEOMETRY OF A CF-252 POINT SOURCE

|     |     |     |     |       |
|-----|-----|-----|-----|-------|
| SPH | 0.0 | 0.0 | 0.0 | 15.0  |
| SPH | 0.0 | 0.0 | 0.0 | 15.05 |
| SPH | 0.0 | 0.0 | 0.0 | 18.3  |
| SPH | 0.0 | 0.0 | 0.0 | 50.0  |
| SPH | 0.0 | 0.0 | 0.0 | 100.0 |
| SPH | 0.0 | 0.0 | 0.0 | 200.0 |
| SPH | 0.0 | 0.0 | 0.0 | 400.0 |
| SPH | 0.0 | 0.0 | 0.0 | 450.0 |
| SPH | 0.0 | 0.0 | 0.0 | 500.0 |

END

|   |    |    |
|---|----|----|
| 1 | +1 |    |
| 2 | +2 | -1 |
| 3 | +3 | -2 |
| 4 | +4 | -3 |
| 5 | +5 | -4 |
| 6 | +6 | -5 |
| 7 | +7 | -6 |
| 8 | +8 | -7 |
| 9 | +9 | -8 |

END

|   |   |   |   |   |   |   |      |   |
|---|---|---|---|---|---|---|------|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1    | 1 |
| 1 | 4 | 4 | 4 | 4 | 4 | 4 | 1000 | 0 |



# BUGLE-80 CROSS SECTION LIBRARY (47N,20G)

|    |    |   |   |    |    |   |   |   |   |   |   |   |
|----|----|---|---|----|----|---|---|---|---|---|---|---|
| 67 | 67 | 0 | 0 | 67 | 70 | 4 | 4 | 6 | 6 | 4 | 2 | 0 |
| 0  | 0  | 0 | 0 | 0  | 0  | 0 | 0 | 0 | 0 | 0 |   |   |

INSERT XSEC HERE

|   |             |
|---|-------------|
| 1 | 46.6800E-2  |
| 1 | -23.3400E-2 |
| 2 | -68.0307E-2 |
| 3 | -54.6350E-2 |
| 4 | 28.8990E-6  |
| 4 | -34.0685E-5 |

## SAMBO ANALYSIS INPUT DATA

|      |   |   |   |   |   |    |   |   |
|------|---|---|---|---|---|----|---|---|
| \$\$ | 5 | 0 | 0 | 0 | 0 | 22 | 1 | 1 |
|------|---|---|---|---|---|----|---|---|

\*\*

|       |     |     |
|-------|-----|-----|
| 18.3  | 0.0 | 0.0 |
| 50.0  | 0.0 | 0.0 |
| 100.0 | 0.0 | 0.0 |
| 200.0 | 0.0 | 0.0 |
| 400.0 | 0.0 | 0.0 |

## GROUP 2 - 3 FLUENCE (NEUTRONS/SOURCE)

\*\*

|     |       |        |
|-----|-------|--------|
| 0.0 | 2R1.0 | 64R0.0 |
|-----|-------|--------|

## GROUP 4 - 5 FLUENCE (NEUTRONS/SOURCE)

\*\*

|       |       |        |
|-------|-------|--------|
| 3R0.0 | 2R1.0 | 62R0.0 |
|-------|-------|--------|

## GROUP 6-7 FLUENCE (NEUTRONS/SOURCE)

\*\*

|       |       |        |
|-------|-------|--------|
| 5R0.0 | 2R1.0 | 60R0.0 |
|-------|-------|--------|

## GROUP 8 FLUENCE (NEUTRONS/SOURCE)

\*\*

|       |     |        |
|-------|-----|--------|
| 7R0.0 | 1.0 | 59R0.0 |
|-------|-----|--------|

## GROUP 9 FLUENCE (NEUTRONS/SOURCE)

\*\*

|       |     |        |
|-------|-----|--------|
| 8R0.0 | 1.0 | 58R0.0 |
|-------|-----|--------|

## GROUP 10 - 15 FLUENCE (NEUTRONS/SOURCE)

\*\*

|       |       |        |
|-------|-------|--------|
| 9R0.0 | 6R1.0 | 52R0.0 |
|-------|-------|--------|

## GROUP 16 - 19 FLUENCE (NEUTRONS/SOURCE)

\*\*

|        |       |        |
|--------|-------|--------|
| 15R0.0 | 4R1.0 | 48R0.0 |
|--------|-------|--------|

## GROUP 20 - 23 FLUENCE (NEUTRONS/SOURCE)

\*\*

|        |       |        |
|--------|-------|--------|
| 19R0.0 | 4R1.0 | 44R0.0 |
|--------|-------|--------|

## GROUP 24 - 26 FLUENCE (NEUTRONS/SOURCE)

```

**
    23R0.0      3R1.0 41R0.0
GROUP 27 FLUENCE (NEUTRONS/SOURCE)
**

    26R0.0      1.0  40R0.0
GROUP 28 FLUENCE (NEUTRONS/SOURCE)
**

    27R0.0      1.0  39R0.0
GROUP 29 - 33 FLUENCE (NEUTRONS/SOURCE)
**

    28R0.0      5R1.0 34R0.0
GROUP 34 - 36 FLUENCE (NEUTRONS/SOURCE)
**

    33R0.0      3R1.0 31R0.0
GROUP 37 - 38 FLUENCE (NEUTRONS/SOURCE)
**

    36R0.0      2R1.0 29R0.0
GROUP 39 - 40 FLUENCE (NEUTRONS/SOURCE)
**

    38R0.0      2R1.0 27R0.0
GROUP 41 - 42 FLUENCE (NEUTRONS/SOURCE)
**

    40R0.0      2R1.0 25R0.0
GROUP 43 - 44 FLUENCE (NEUTRONS/SOURCE)
**

    42R0.0      2R1.0 23R0.0
GROUP 45 - 46 FLUENCE (NEUTRONS/SOURCE)
**

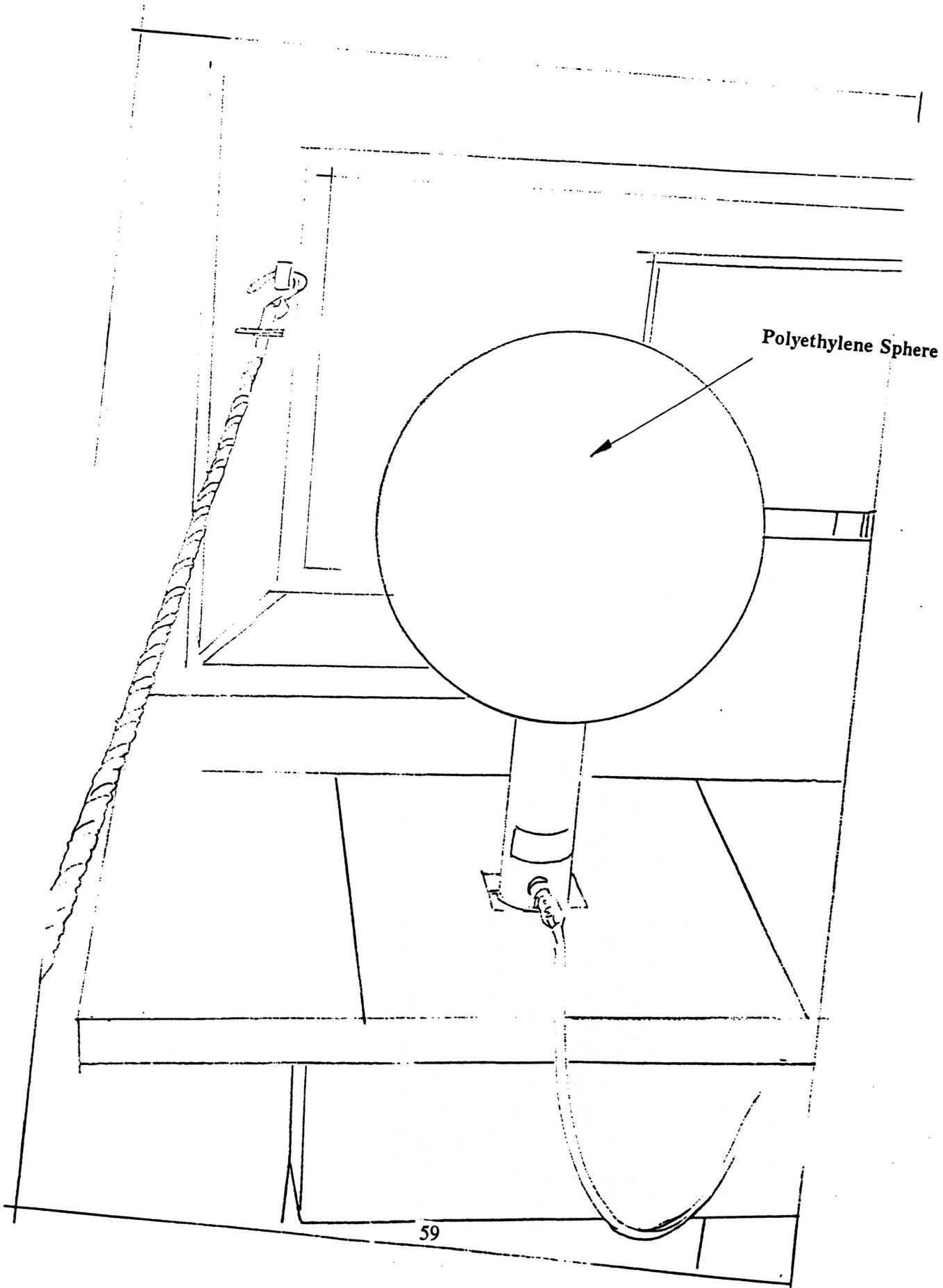
    44R0.0      2R1.0 21R0.0
GROUP 47 FLUENCE (NEUTRONS/SOURCE)
**

    46R0.0      1.0  20R0.0
NEUTRON EQUIVALENT DOSE (GROUP 1-28), MREM/SOURCE NEUTRON
**
5.7280E-5 5.0880E-5 4.7940E-5 7.5390E-5 4.3560E-5 4.1280E-5 3.9910E-5 4.1100E-5
3.9850E-5 3.8410E-5 3.7600E-5 3.7060E-5 3.6880E-5 3.6670E-5 3.6040E-5 3.6010E-5
3.6300E-5 3.4760E-5 3.2440E-5 3.0340E-5 2.8720E-5 2.6610E-5 2.2670E-5 1.8210E-5
1.4190E-5 9.6500E-6 6.1520E-6 3.7720E-6 49E0.0
NEUTRON EQUIVALENT DOSE (GROUP 29-44), MREM/SOURCE NEUTRON
**
28E0.0 2.5430E-6 2.0650E-6 1.7920E-6 1.6550E-6 1.3620E-6 9.2490E-7 9.0770E-7
9.3530E-7 9.4980E-7 1.0610E-6 1.0900E-6 1.1210E-6 1.1510E-6 1.1650E-6 1.1750E-6
1.1790E-6 23E0.0
NEUTRON EQUIVALENT DOSE (GROUP 45-47), MREM/SOURCE NEUTRON
**
44E0.0 1.1140E-6 1.0400E-6 8.0000E-7 20E0.0

```

## **Appendix C**

Photographs of the instrumentations and equipment setups used in the experiment.



Polyethylene Sphere

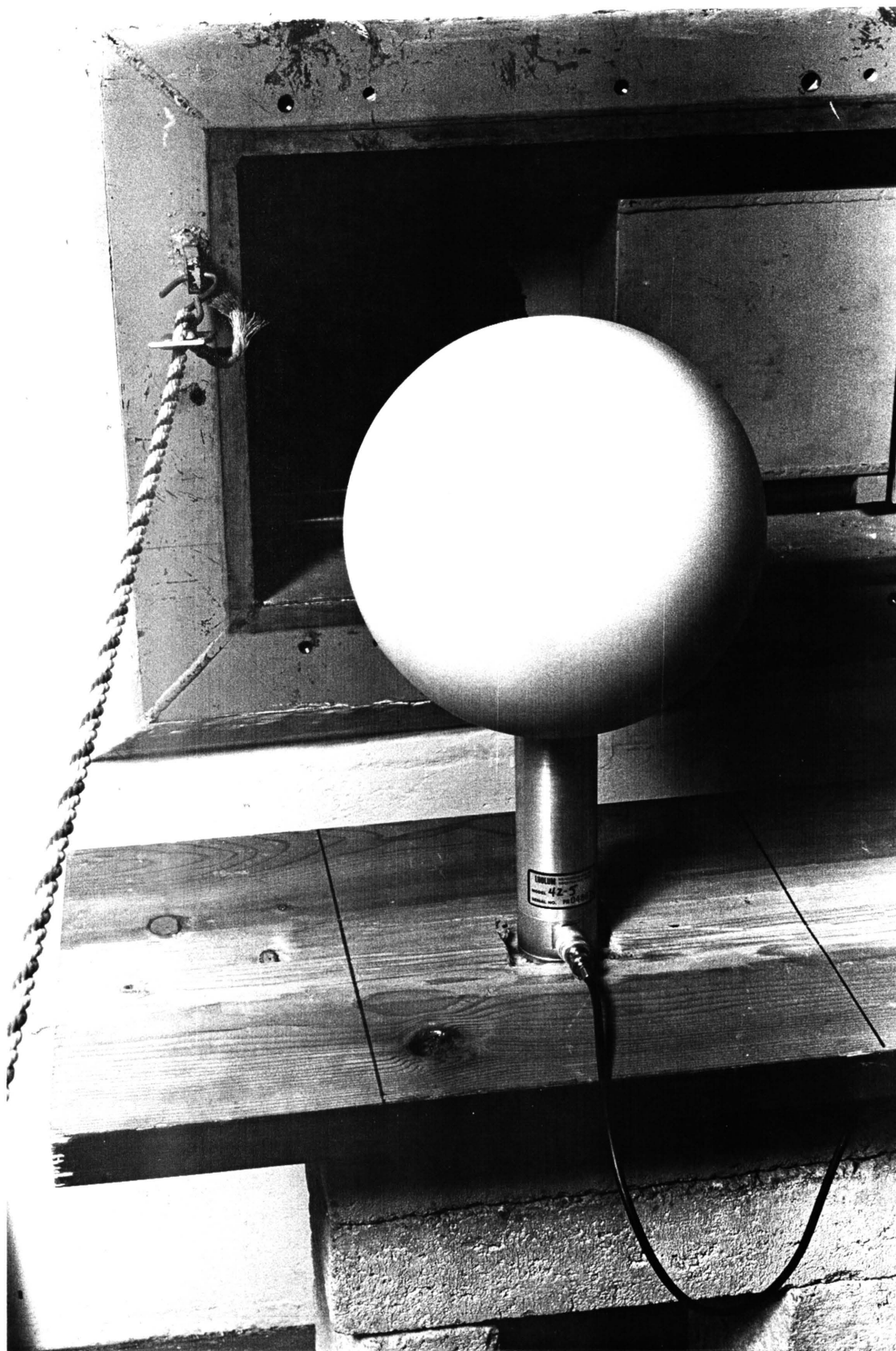
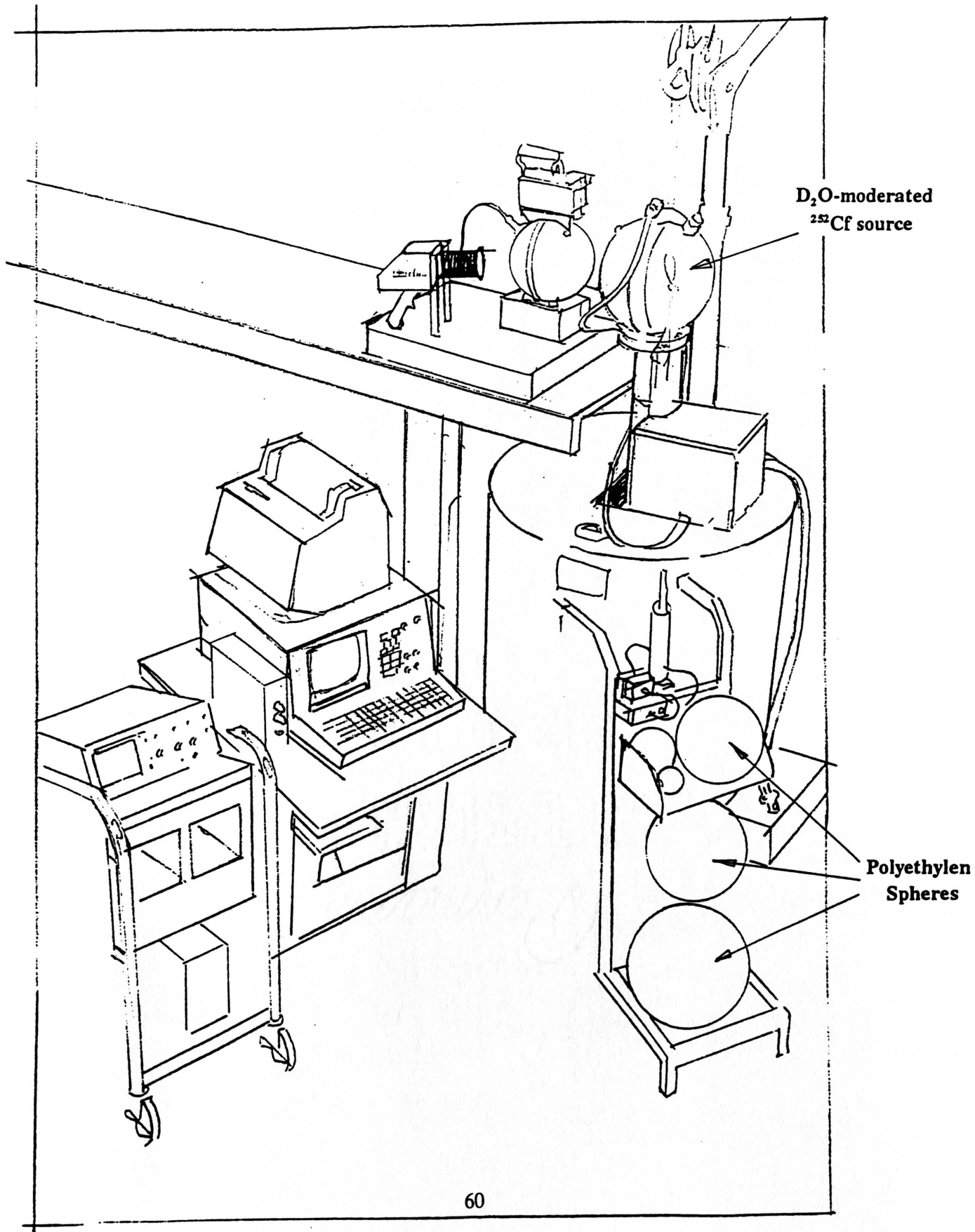


Figure C.1. The photograph of a Bonner Sphere setup at the TRIGA tangential beam port.



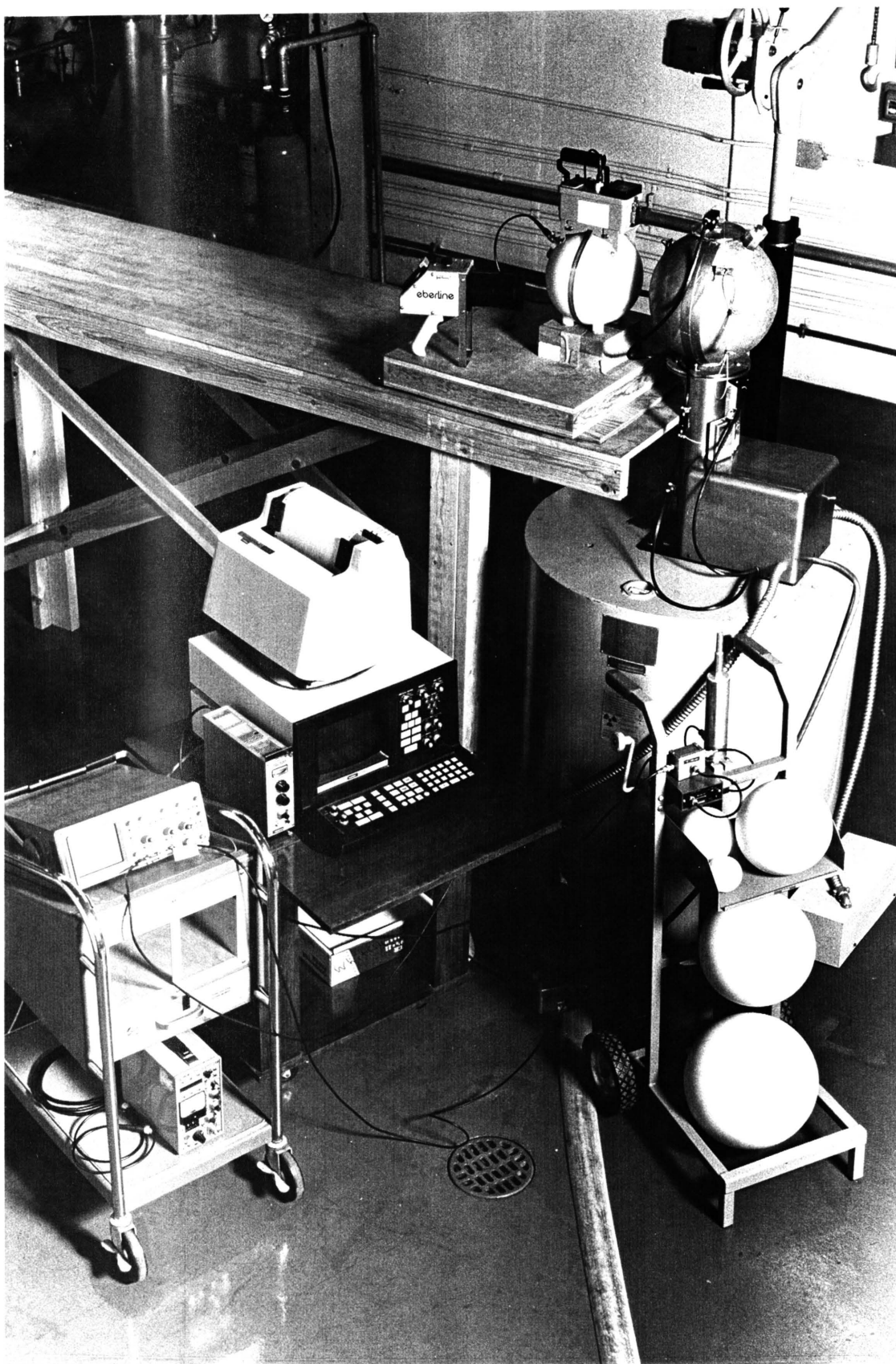
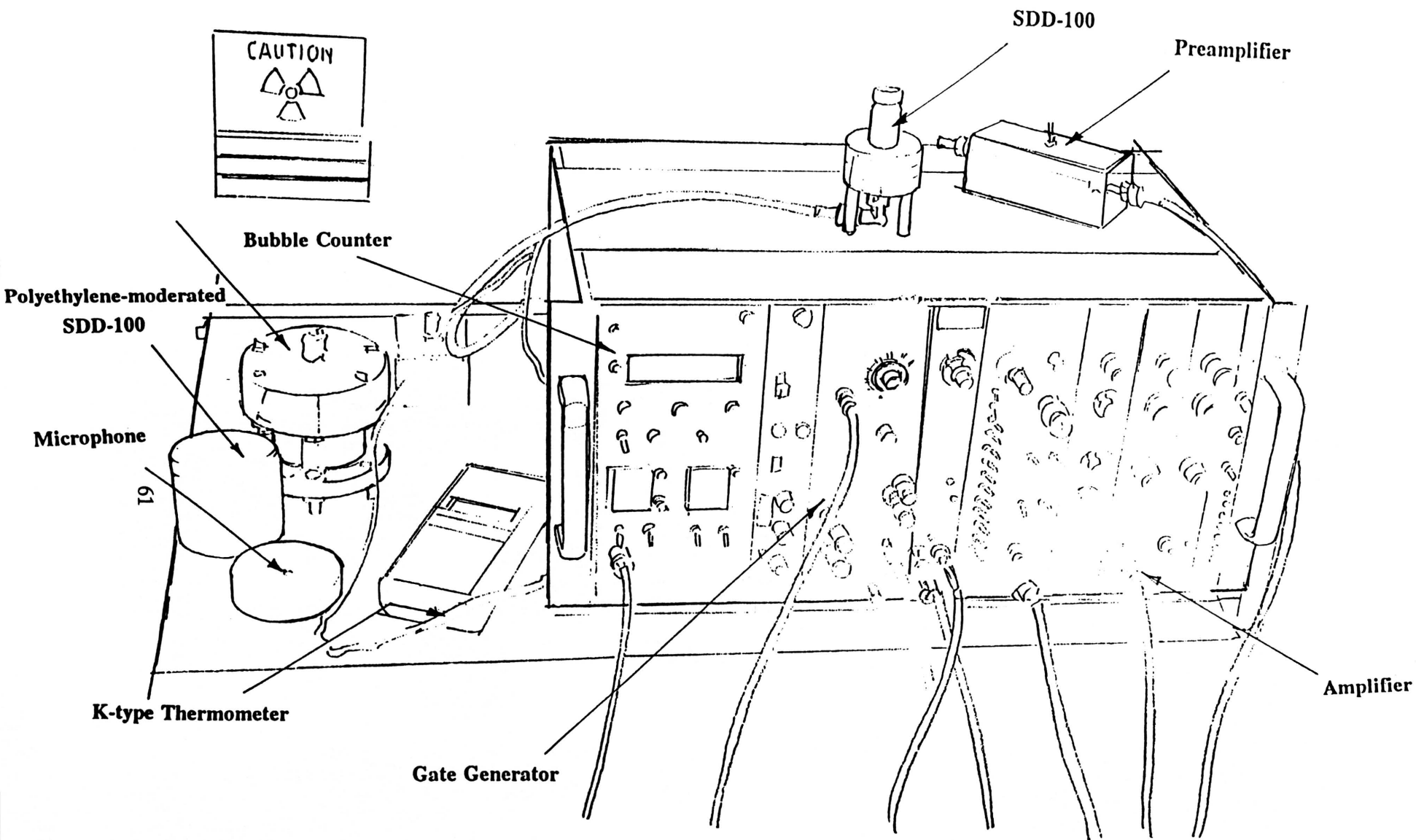


Figure C.2. The photograph of the Bonner Sphere System and the  $D_2O$ .





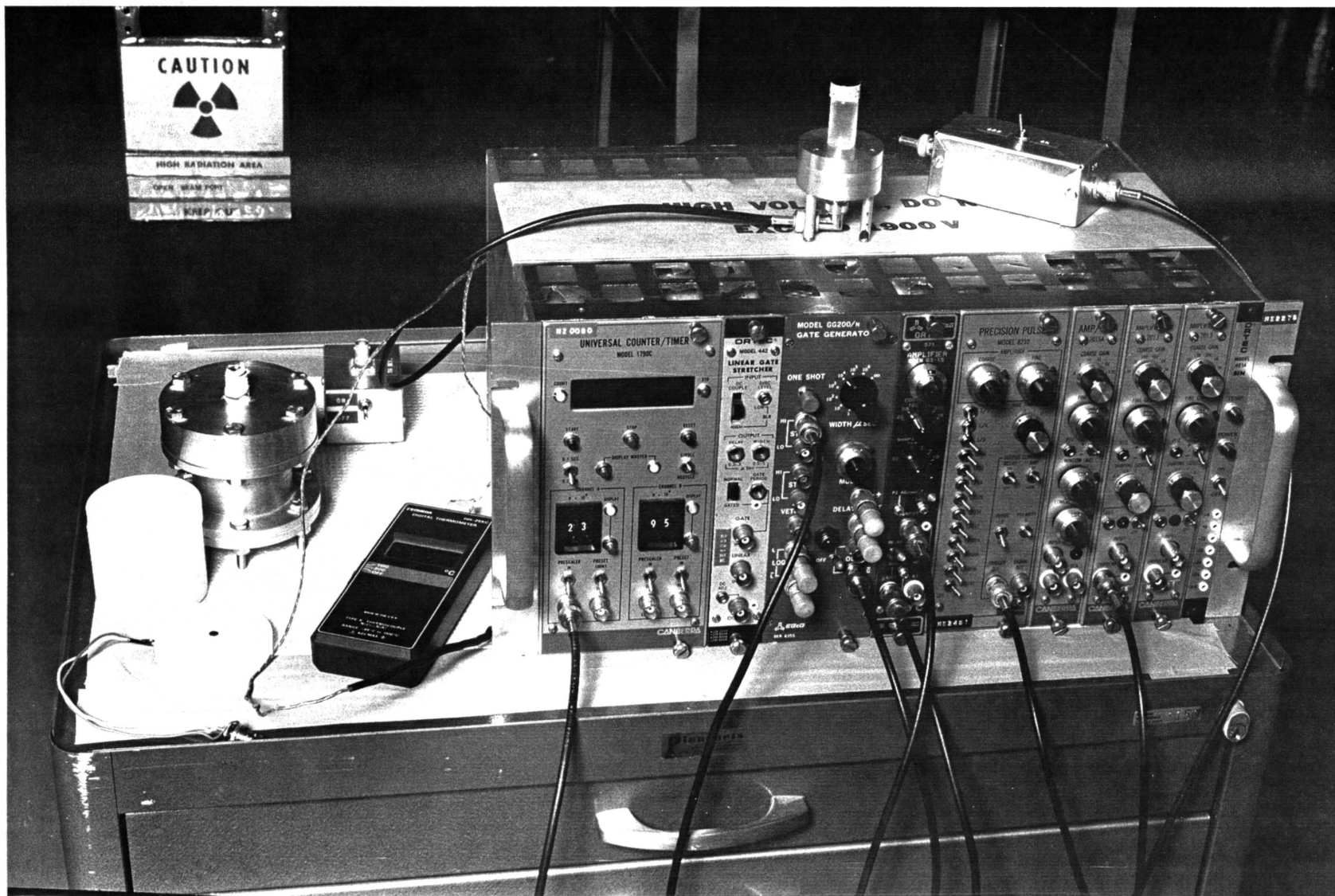
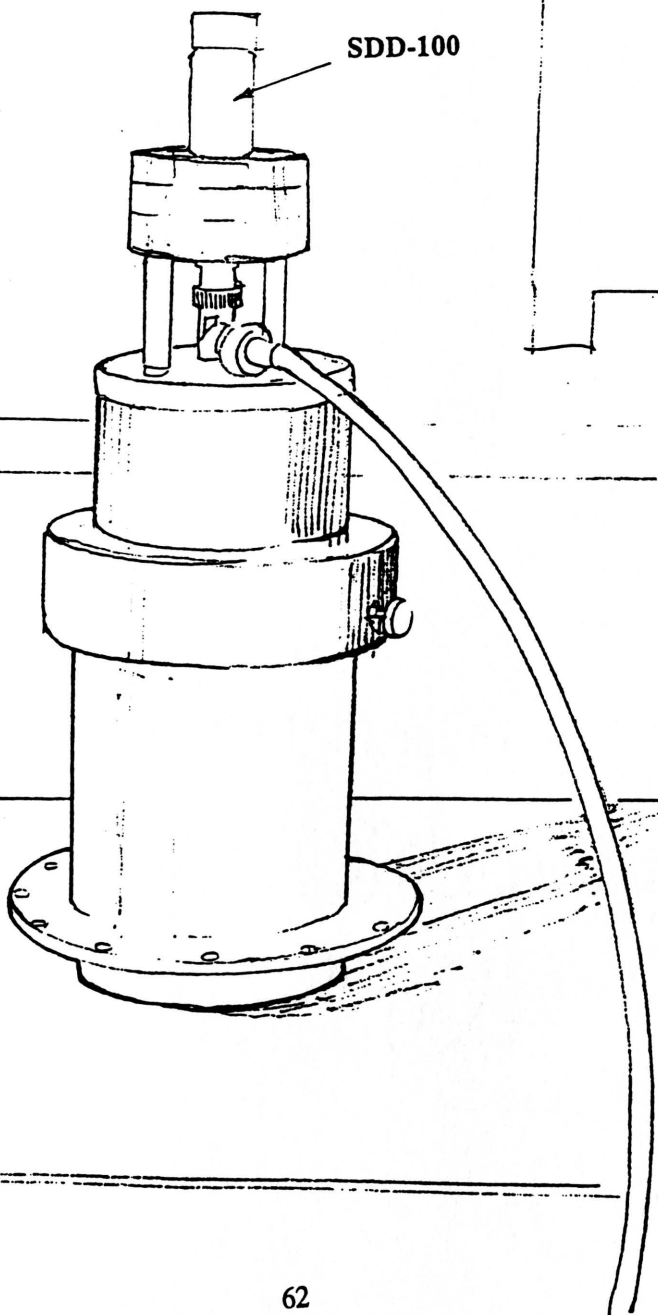


Figure C.3. The photograph of the electronic modules of the bubble counting system.



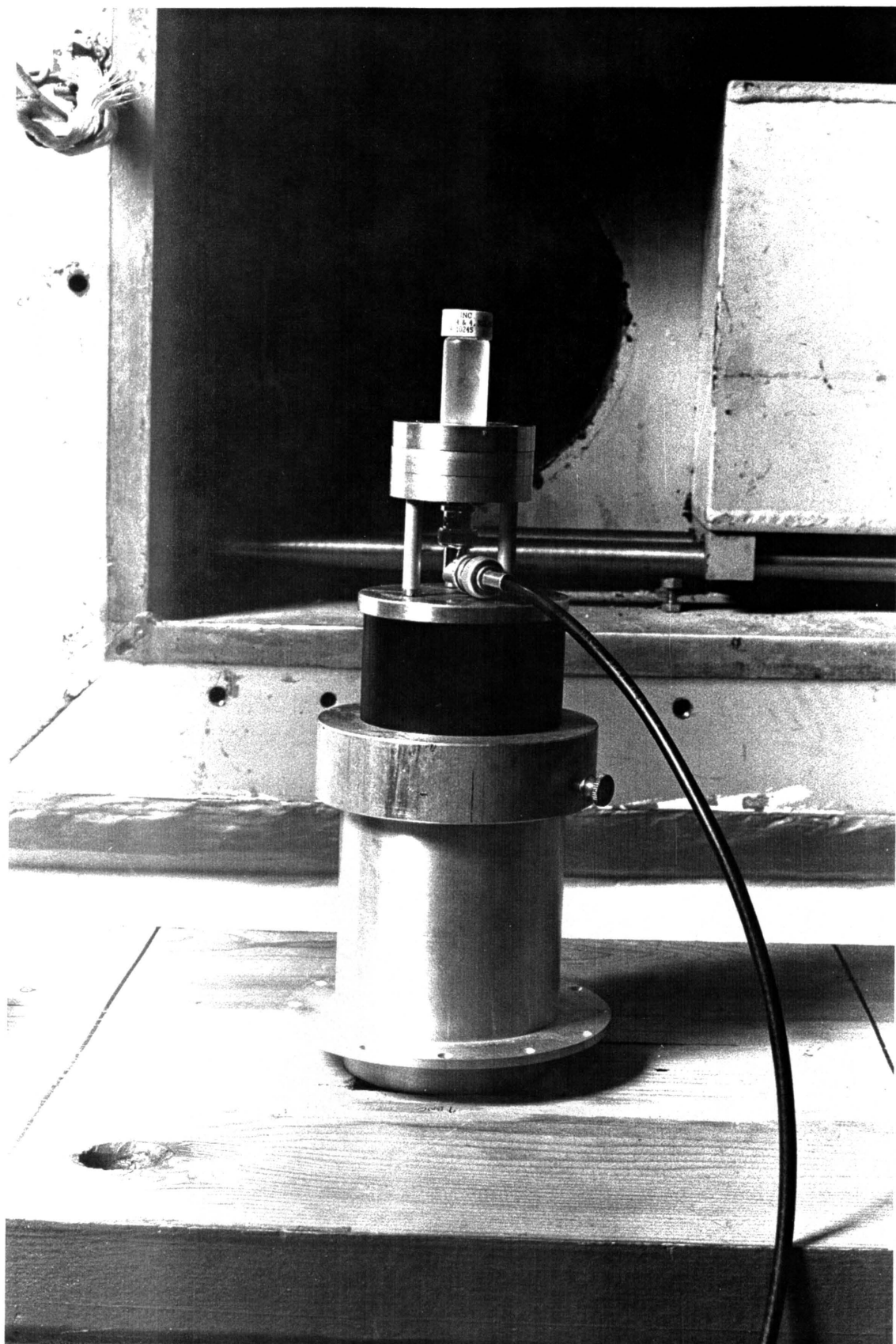


Figure C.4. The photograph of the experimental setup for a SDD-100 at the TRIGA tangential beam port.

## **Appendix D**

### **Raw Data**

Raw data of the SDD-100 for the neutron sources

**Table D1**

Source: Pu-Be  
 Distance (Source to Detector): 30 cm  
 Source Serial #: SDD-100-4-10245  
 Mean Temperature (Source): 22.7 °C

Dose Equivalent: 2.171 bubbles· $\mu$ Sv<sup>-1</sup>  
 Droplet Depletion Correction Factor: 1.012  
 Detector: Bare SDD-100

| Time Interval (min) | Temperature (oC) | Bubble Count | Bubble Count After Correction |
|---------------------|------------------|--------------|-------------------------------|
| 0 - 5               | 23.7             | 38           | 38                            |
| 5 - 10              | 23.2             | 67           | 68                            |
| 10 - 15             | 22.9             | 106          | 107                           |
| 15 - 20             | 22.7             | 144          | 146                           |
| 20 - 25             | 22.6             | 175          | 177                           |
| 25 - 30             | 22.5             | 209          | 211                           |
| 30 - 35             | 22.5             | 242          | 245                           |
| 35 - 40             | 22.5             | 272          | 275                           |
| 40 - 45             | 22.5             | 305          | 309                           |
| 45 - 50             | 22.4             | 335          | 339                           |
| 50 - 55             | 22.5             | 361          | 365                           |
| 55 - 60             | 22.5             | 399          | 404                           |

**Table D2**

Source: Pu-Be

Distance (Source to Detector): 30 cm

Source Serial #: SDD-100-4-10245

Mean Temperature (Source): 23.1 °C

Dose Equivalent: 1.552 bubbles· $\mu$ Sv<sup>-1</sup>

Droplet Depletion Correction Factor: 1.012

Detector: Polyethylene-moderated SDD-100

| Time Interval (min) | Temperature (oC) | Bubble Count | Bubble Count After Correction |
|---------------------|------------------|--------------|-------------------------------|
| 0 - 5               | 23.2             | 31           | 32                            |
| 5 - 10              | 23.2             | 55           | 56                            |
| 10 - 15             | 23.2             | 83           | 85                            |
| 15 - 20             | 23.1             | 108          | 110                           |
| 20 - 25             | 23.1             | 142          | 145                           |
| 25 - 30             | 23.1             | 173          | 177                           |
| 30 - 35             | 23.0             | 201          | 205                           |
| 35 - 40             | 23.0             | 233          | 238                           |
| 40 - 45             | 23.0             | 260          | 266                           |
| 45 - 50             | 23.0             | 283          | 289                           |
| 50 - 55             | 22.9             | 305          | 311                           |
| 55 - 60             | 22.9             | 330          | 337                           |

**Table D3**

Source: Cf-D<sub>2</sub>O Moderated  
 Distance (Source to Detector): 100 cm  
 Source Serial #: SDD-100-4-10245  
 Mean Temperature (Source): 24.0 °C

Dose Equivalent: 2.615 bubbles·μSv<sup>-1</sup>  
 Droplet Depletion Correction Factor: 1.03  
 Detector: Bare SDD-100

| Time Interval (min) | Temperature (oC) | Bubble Count | Bubble Count After Correction |
|---------------------|------------------|--------------|-------------------------------|
| 0 - 5               | 24.0             | 29           | 30                            |
| 5 - 10              | 24.0             | 61           | 63                            |
| 10 - 15             | 24.0             | 88           | 91                            |
| 15 - 20             | 24.0             | 108          | 111                           |
| 20 - 25             | 24.0             | 130          | 134                           |
| 25 - 30             | 24.0             | 154          | 159                           |
| 30 - 35             | 24.0             | 174          | 179                           |
| 35 - 40             | 24.0             | 199          | 205                           |
| 40 - 45             | 24.0             | 224          | 231                           |
| 45 - 50             | 24.0             | 253          | 261                           |
| 50 - 55             | 24.0             | 272          | 280                           |
| 55 - 60             | 24.0             | 298          | 307                           |

**Table D4**

Source: Cf-D<sub>2</sub>O Moderated  
 Distance (Source to Detector): 30 cm  
 Source Serial #: SDD-100-4-10245  
 Mean Temperature (Source): 24.2 °C

Dose Equivalent: 1.831 bubbles·μSv<sup>-1</sup>  
 Droplet Depletion Correction Factor: 1.037  
 Detector: Polyethylene-moderated SDD-100

| Time Interval (min) | Temperature (oC) | Bubble Count | Bubble Count<br>After Correction |
|---------------------|------------------|--------------|----------------------------------|
| 0 - 5               | 24.1             | 15           | 16                               |
| 5 - 10              | 24.1             | 30           | 31                               |
| 10 - 15             | 24.2             | 51           | 53                               |
| 15 - 20             | 24.2             | 70           | 73                               |
| 20 - 25             | 24.2             | 87           | 90                               |
| 25 - 30             | 24.2             | 108          | 112                              |
| 30 - 35             | 24.2             | 128          | 133                              |
| 35 - 40             | 24.2             | 147          | 152                              |
| 40 - 45             | 24.2             | 159          | 165                              |
| 45 - 50             | 24.2             | 172          | 178                              |
| 50 - 55             | 24.2             | 190          | 197                              |
| 55 - 60             | 24.1             | 207          | 215                              |



**Table D5**

Source: Tangential Al-Filter  
 Distance (Source to Detector): 50 cm  
 Source Serial #: SDD-100-4-10245  
 Mean Temperature (Source): 23.5 °C

Dose Equivalent: 1.408 bubbles· $\mu$ Sv<sup>-1</sup>  
 Droplet Depletion Correction Factor: 1.044  
 Detector: Bare SDD-100

| Time Interval (min) | Temperature (oC) | Bubble Count | Bubble Count After Correction |
|---------------------|------------------|--------------|-------------------------------|
| 0 - 5               | 23.4             | 11           | 11                            |
| 5 - 10              | 23.4             | 31           | 32                            |
| 10 - 15             | 23.4             | 40           | 42                            |
| 15 - 20             | 23.4             | 60           | 63                            |
| 20 - 25             | 23.4             | 88           | 92                            |
| 25 - 30             | 23.5             | 107          | 112                           |
| 30 - 35             | 23.5             | 125          | 130                           |
| 35 - 40             | 23.5             | 146          | 152                           |
| 40 - 45             | 23.5             | 155          | 162                           |
| 45 - 50             | 23.5             | 168          | 175                           |
| 50 - 55             | 23.5             | 184          | 192                           |
| 55 - 60             | 23.5             | 200          | 209                           |
| 60 - 65             | 23.5             | 218          | 228                           |
| 65 - 70             | 23.5             | 238          | 248                           |

Table D6

Source: Tangential Al-Filter  
 Distance (Source to Detector): 50 cm  
 Source Serial #: SDD-100-4-10245  
 Mean Temperature (Source): 23.7 °C

Dose Equivalent: 1.448 bubbles· $\mu$ Sv<sup>-1</sup>  
 Droplet Depletion Correction Factor: 1.051  
 Detector: Polyethylene-moderated SDD-100

| Time Interval (min) | Temperature (oC) | Bubble Count | Bubble Count After Correction |
|---------------------|------------------|--------------|-------------------------------|
| 0 - 5               | 23.8             | 22           | 23                            |
| 5 - 10              | 23.8             | 38           | 40                            |
| 10 - 15             | 23.8             | 59           | 62                            |
| 15 - 20             | 23.8             | 71           | 75                            |
| 20 - 25             | 23.8             | 81           | 85                            |
| 25 - 30             | 23.8             | 92           | 97                            |
| 30 - 35             | 23.8             | 111          | 117                           |
| 35 - 40             | 23.8             | 125          | 131                           |
| 40 - 45             | 23.8             | 141          | 148                           |
| 45 - 50             | 23.7             | 164          | 172                           |
| 50 - 55             | 23.7             | 183          | 192                           |
| 55 - 60             | 23.7             | 206          | 217                           |
| 60 - 65             | 23.5             | 222          | 233                           |
| 65 - 70             | 23.5             | 243          | 255                           |

**Table D7**

Source: Thermal Column  
 Distance (Source to Detector): 50 cm  
 Source Serial #: SDD-100-4-10245

Dose Equivalent: 2.800 bubbles· $\mu$ Sv<sup>-1</sup>  
 Droplet Depletion Correction Factor: 1.060  
 Detector: Bare SDD-100

| Time Interval (min) | Bubble Count | Bubble Count<br>After Correction |
|---------------------|--------------|----------------------------------|
| 0 - 5               | 39           | 41                               |
| 5 - 10              | 66           | 70                               |
| 10 - 15             | 95           | 101                              |
| 15 - 20             | 124          | 131                              |
| 20 - 25             | 153          | 162                              |
| 25 - 30             | 172          | 182                              |
| 30 - 35             | 189          | 200                              |
| 35 - 40             | 217          | 230                              |
| 40 - 45             | 242          | 256                              |
| 45 - 50             | 264          | 280                              |

**Table D8**

Source: Thermal Column

Distance (Source to Detector): 50 cm

Source Serial #: SDD-100-4-10245

Dose Equivalent: 1.841 bubbles· $\mu$ Sv<sup>-1</sup>

Droplet Depletion Correction Factor: 1.065

Detector: Polyethylene-moderated SDD-100

| Time Interval (min) | Bubble Count | Bubble Count<br>After Correction |
|---------------------|--------------|----------------------------------|
| 0 - 5               | 14           | 15                               |
| 5 - 10              | 29           | 31                               |
| 10 - 15             | 48           | 51                               |
| 15 - 20             | 62           | 66                               |
| 20 - 25             | 78           | 83                               |
| 25 - 30             | 92           | 98                               |
| 30 - 35             | 107          | 114                              |
| 35 - 40             | 117          | 125                              |
| 40 - 45             | 134          | 143                              |
| 45 - 50             | 146          | 156                              |
| 50 - 55             | 158          | 168                              |
| 55 - 60             | 173          | 184                              |

# Experimental Confirmation of an Improved Neutron Dosimeter Using Superheated Liquid Drops

by

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B.S., São Paulo Catholic University, 1979

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## AN ABSTRACT OF A THESIS

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## Abstract

The Superheated Drop Detector (SDD) is a new kind of neutron detector. Its operation is based on the same principle as that of a bubble chamber: namely, the initiation of vapor bubbles by energetic ions in superheated liquids. A SDD consists of a large number of superheated droplets liquid uniformly distributed in a soft gel. The volume of vapor, or the acoustic waves given out when superheated drops vaporize, can serve as a measure of neutron intensity.

SDD-100<sup>+</sup> is the most widely used neutron dosimeter because it was claimed to be nearly dose-equivalent.

In this study, we experimentally investigated the neutron response function of SDD-100 and a polyethylene-moderated SDD-100, and compare then with the ICRP neutron-fluence-to-dose-equivalent conversion curve. Our experimental results confirmed the results predicted by Monte Carlo calculations and they are summarized as follows: On the basis of bubbles· $\mu\text{Sv}^{-1}$  in a free field. The bare SDD-100 favorably responds to thermal neutrons and neutrons with energies between 70 and 700 keV, and it does not respond as well to several-MeV neutrons, and it responds most poorly to neutrons with energies between 1 keV and 50 keV. The polyethylene-moderated SDD-100 responds more equally to all neutrons with energies between thermal and 10 MeV, and therefore it is more dose-equivalent than a bare SDD-100.

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<sup>+</sup> Trademark of Apfel Enterprises