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CHARACTERISATION OF THE HARSHAW ALBEDO TLD AND THE BUBBLE DETECTORS BD-100R AND BDS-1500

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Abstract — A combination type personnel neutron dosemeter (CPND) consisting of one Harshaw albedo TLD and two bubble detectors (one BD-100R and one BDS-1500) has been developed. The dosimetric characteristics of the CPND's three detector components were investigated comprehensively. The characteristics studied were the re-usability, linearity, lower limit of detection, detection capability in mixed neutron–gamma fields, angular dependence, and neutron energy dependence. The experimental methods and the results, which show that the CPND has good dosemeter properties, are presented.

INTRODUCTION

A new combination personnel neutron dosemeter (CPND) has been developed at the Oak Ridge National Laboratory (ORNL). The CPND consists of a new Harshaw albedo thermoluminescence dosemeter (TLD)(1) and two bubble detectors (one BD-100R and one BDS-1500)*. These three detector components were characterised comprehensively to examine the capabilities and limitations of the CPND in the following areas: re-usability, linearity, lower limit of detection, detection capability in mixed neutron–gamma fields, angular dependence, and neutron energy dependence. This paper presents, in sequence, the experimental methods and the results of the characteristics investigation for the albedo TLD and the bubble detectors.

MATERIALS

Figure 1 shows the Harshaw albedo TLD design. The aluminium card ($43\times31\times1$ mm^3) has four holes to contain two pairs of TLD-600/TLD-700 chips ($3.2\times3.2\times0.9$ mm^3) which are encapsulated between two thin sheets of Teflon. The aluminium card and cadmium sheet ($28\times13\times0.46$ mm^3) are inside a plastic holder ($62\times41\times6$ mm^3). One pair of TLD-600/TLD-700 (elements 1 and 2, respectively) is shielded in front by the cadmium sheet. The TLD-700 elements are used to estimate the photon signals of their paired TLD-600 elements. The Cd-covered TLD-600 (element 1) detects mainly albedo neutrons and its neutron signal is called reading A. The other TLD-600 (element 4) detects both albedo and incident neutrons and its neutron signal is called reading T.

The photon sensitivities of the four elements for all TLD cards were individually calibrated using a ^{137}Cs irradiation with the element correction coefficient (ECC) method(1), which corrects for the non-uniform sensitivity within the TLD batch. The four elements of the card are read simultaneously in the Harshaw 8800 reader. The long-term stabilities of the four reader channels were traced and

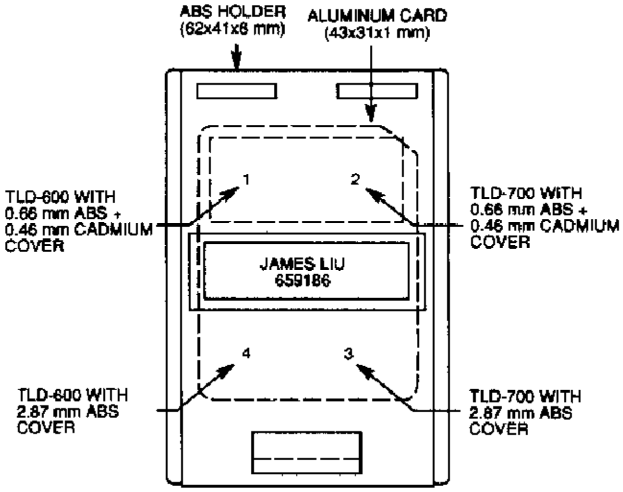

Figure 1. The Harshaw albedo neutron TLD design. ABS = acrylonitrile butadiene styrene.

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** BD-100R and BDS-1500 are trademarks of Bubble Technology Industries, Highway 17, Chalk River, Ontario, K0J 0J1, Canada.

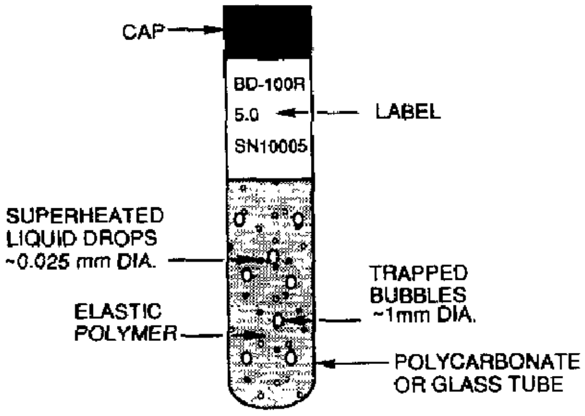

Figure 2. Illustration of the bubble detector. The microscopic drops are uniformly distributed in the polymer. The cylindrical tube (1.6 cm diam., 8 cm height) holds the nearly transparent mixture. When a neutron hits the drop, the drop vaporises to become a visible bubble.

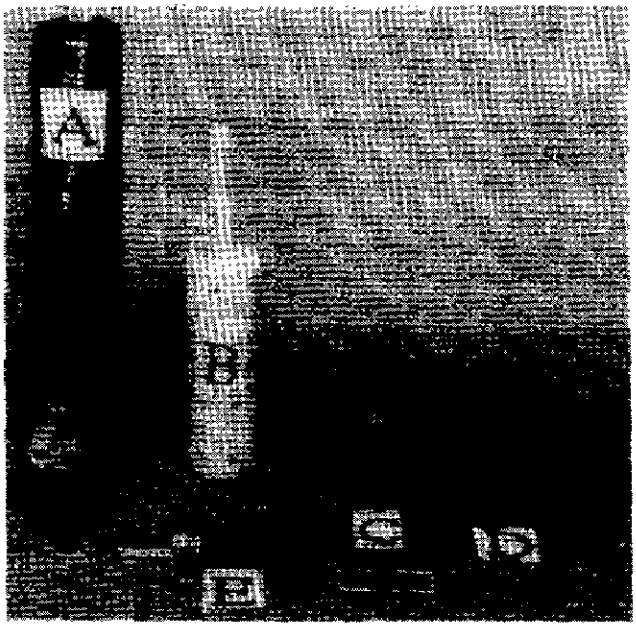

Figure 3. The recompression chamber (A–D four parts) and two personal recompression devices (E).

corrected by the use of reader calibration factors (RCFs)(1), which convert and normalise all TL signals (nC) to a constant ^{137}Cs exposure at ORNL. Both neutron readings A and T are corrected by ECC, RCF, and photon signal subtraction (TLD-600 minus TLD-700) and are in units of mR, a generic unit used at ORNL for all TL signals.

Figure 2 shows the bubble detector from Bubble Technology Industries (BTI), Canada. The BD-100R and BDS-1500 have nominal threshold energies around 100 keV and 1500 keV, respectively. The detector consists of thousands of tiny superheated liquid drops dispersed uniformly in an elastic polymer inside a glass vial (diameter 16 mm and height 80 mm). The sensitivity is adjustable depending on the number of drops inside the vial. The normal sensitivity range produced is 0.1–1 bubbles per μSv for the BD-100R and 0.1–0.5 bubbles per μSv for the BDS-1500. The number of bubbles (abbreviated as bu in this paper) is the bubble detector (BD) reading.

IRRADIATIONS

All irradiations, unless otherwise specified, were conducted at ORNL's new Radiation Calibration Laboratory (RADCAL). RADCAL is a part of the Dosimetry Application Research facility and its capabilities have been documented(2). The ^{252}Cf source moderated by a 15 cm radius polyethylene sphere or by a 15 cm radius D_2O sphere covered with a cadmium shell is hereafter referred to as ^{252}Cf(PE) and ^{252}Cf(D_2O), respectively. The californium source was in the concrete walled neutron room (9.1×8.7×6.1 m^3) with a height of 1.8 m for irradiation. A ^{238}Pu–Be source (height 1.4 m) can be used either in the neutron room or in the aluminium walled room. Unless otherwise specified, all irradiations were performed with the TLDs and BDs mounted on a standard Lucite slab phantom of the size 40×40×15 cm^3 and with the radiation perpendicularly incident on the dosemeters and a source-to-phantom distance of 50 cm. ICRP 21 neutron dose equivalent quantity(3) was used for the calibration.

RE-USABILITY

Albedo TLD

The re-usability of the new albedo TLD using the reader anneal technique has been studied and the detailed results have been published(4). The conclusion from that study(4) is that, using the heating profiles suggested by Harshaw and the TL signals from certain regions of interest (peaks 3, 4, and 5), the individual TL element sensitivity variations (1σ) associated with re-use are <5%.

Bubble detector (BD)

Utilising the personal recompression device or the recompression chamber (see Figure 3) to recompress the gas bubbles into drops, the BD becomes re-usable. The two main purposes in studying the re-usability of the BDs were (a) to examine the sensitivity stability of both the BD-100R and the BDS-1500 over re-use and their usable lifetimes, and (b) to optimise the operational usage procedure, regarding the recompression (i.e. re-use) period and conditions.

The re-usability study procedures and the results are presented in the Appendix. The re-usability tests, as well as the authors' experience from the use of the BDs in other experiments, showed the following:

1. The more frequently the BD is recompressed, the longer the lifetime and the better the stability of the BD during re-use.
2. Most of the BDs, if recompressed at least weekly, can be re-used for at least three months with satisfactory stability (1σ ~ 20%). The sensitivity variation during re-use is primarily due to expected statistical variations.
3. Many BDs have been used for over seven months with no indication of sensitivity loss.
4. A few BDs, especially the low sensitivity BD, did have a sensitivity drop problem, and a sensitivity correction would be required if those BDs were to continue to be used.
5. All bubbles formed were able to be recompressed throughout the 7 month study period.
6. Similar stability results between this study and other authors' results[5-7] using different hydraulic pressures and recompression durations also indicated that the pressure and duration of recompression do not affect the BD sensitivity variations during re-use.
7. There was no bubble fading problem for a nine month period after irradiation.

LINEARITY

Albedo TLD

The linearity of the albedo TLD was examined with the ^{252}Cf(PE) irradiations and the results are shown in Figure 4. Four TLDs as a group were irradiated to a certain dose equivalent and the mean readings A and T were plotted against the neutron dose equivalent which varied from 0.05 mSv to 3.0 mSv. A least squares linear fit gave the r^2 (square of correlation coefficient) values and the slope (sensitivity). The r^2 values of the mean readings A and T were both equal to 1.000. The 1σ values of the mean readings A and T were less than 5%. These results show the linearity of the albedo TLD.

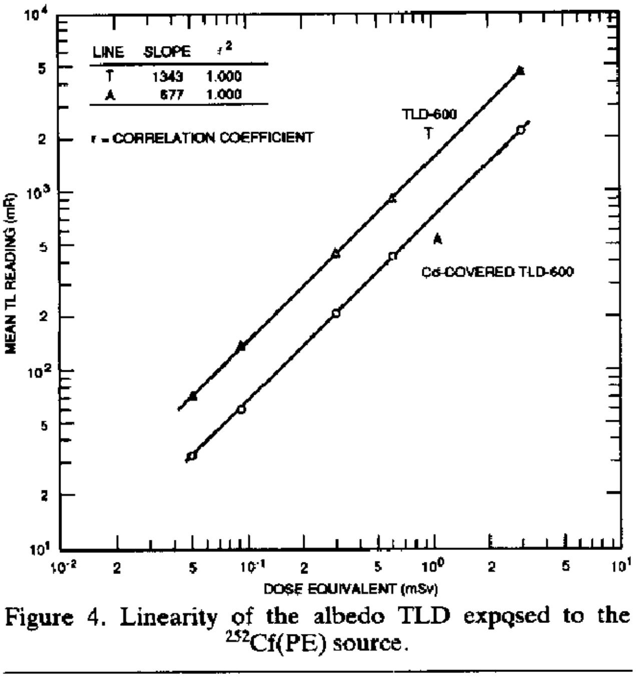

Figure 4. Linearity of the albedo TLD exposed to the ^{252}Cf(PE) source.

Line	Slope	r^2
T	1343	1.000
A	677	1.000

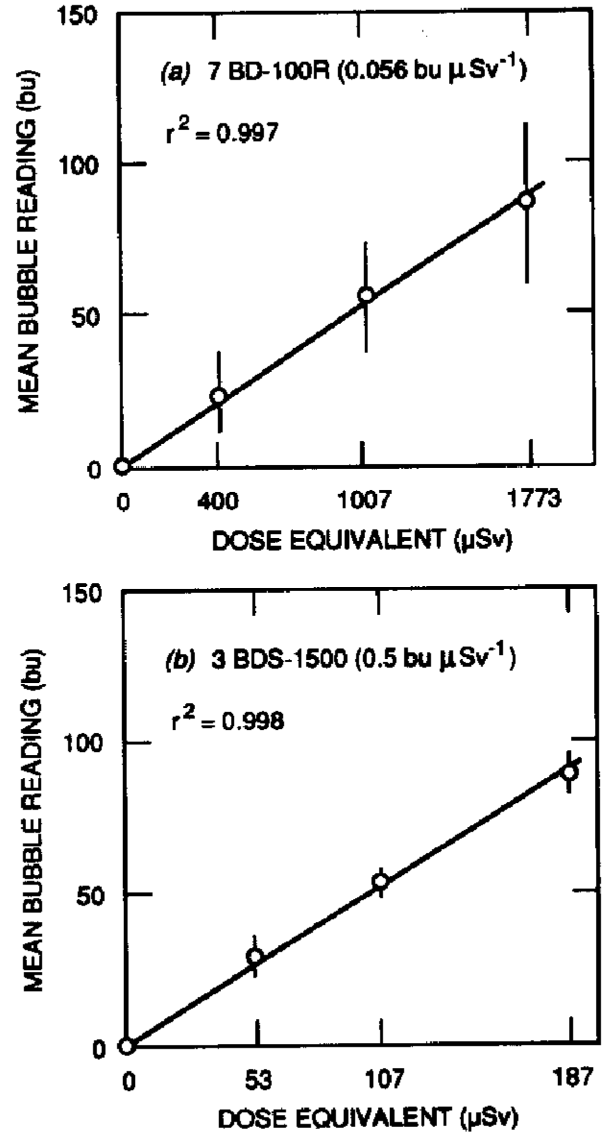

Figure 5. Linearity of the bubble detectors exposed to the ^{238}Pu–Be source. (a) Seven BD-100 R (0.056 bu.μSv^{-1}), r^2 = 0.997. (b) Three BDS-1500 (0.5 bu.μSv^{-1}), r^2 = 0.998.

Bubble detector

Seven BD-100R and three BDS-1500 bubble detectors were irradiated with the ^{238}Pu–Be source, and were counted and recompressed on the second day after exposure. The above procedure was repeated several times for three dose equivalent levels. The linearity results for the BDs are plotted as the mean bubble reading against the dose equivalent in Figure 5. Since no bubble was observed for an unexposed BD, the point (0,0) was granted as a theoretical point and was included in the least squares linear fit analysis. The r^2 values (0.997 for the BD-100R and 0.998 for the BDS-1500) show the linearity of the BD over the range of 20–90 bubbles. The 1σ values were larger for smaller dose equivalents. This was due more to the statistical variations in the small number of bubbles than to non-linearity. The large 1σ values for the BD-100R were due to the non-uniform sensitivity of the BD batch.

Perks *et al*(8) showed a linearity up to about 400 bubbles for the BD-100 by using a photograph bubble counting method. Ipe and Busick(9) had similar BD-100 linearity results as obtained in this study for the BD-100R and BDS-1500, because of the similar monitor–magnify counting method used. Therefore, it can be concluded that within the limits of statistical error the neutron reading of the BD is linear. The upper limit of the linear range is governed by the maximum number of bubbles that can be counted accurately and efficiently by the bubble counting system. The monitor–magnify counting system, which has better resolution to distinguish overlapping bubbles at high dose levels, has a higher linear range than the eye counting method. Experience shows that the optimum number of bubbles which can be counted by eye with least error and trouble is around 50–70.

LOWER LIMIT OF DETECTION (LLD)

A US Department of Energy (DOE) Order(10) requires that the dosemeter be provided to those persons who are likely to receive an effective dose equivalent exceeding 1 mSv in a year from external sources. This implies that a dosemeter's LLD should be no greater than 250 μSv, if exchanged quarterly.

Albedo TLD

The determination of the LLD for the albedo TLD basically followed the procedure specified in the DOE Laboratory Accreditation Program (DOELAP) Standard(11). Ten TLDs were annealed and put on a phantom for storage in the natural background environment for 94 days (close to the quarterly TLD exchange period at ORNL). After storage, the 10 TLDs were processed and evaluated to determine the background dose equivalent values. The LLD was then calculated according to the LLD equation in the DOELAP Standard(11). The LLD was 92 μSv for ^{252}Cf and 10 μSv for ^{252}Cf(D$_2$O) for a three month exchange schedule. The low LLD can be attributed to the successful use of the ECC correction which greatly reduces the sensitivity variations within the TLD batch.

Bubble detector

For the highest sensitivity BD used in the study (0.82 bu.μSv^{-1} for the BD-100R and 0.45 bu.μSv^{-1} for the BDS-1500), the background count in a week was observed to be 0–4 for the BD-100R and 0–2 for the BDS-1500. Therefore, the LLD for the highest sensitivity BD is no greater than 5 μSv for a weekly re-use schedule and the LLD for one quarter would be 65 μSv. For the lower sensitivity BD, the background count in a week was genreally zero. Therefore, the LLD for the lower sensitivity BD is the dose equivalent corresponding to a reading of one bubble.

DETECTION CAPABILITY IN MIXED NEUTRON–GAMMA FIELDS

Genrally, smaller H_n/H_γ (neutron/gamma dose equivalent ratio) results in a less accurate neutron dose equivalent estimate. The regulations require that the neutron dose equivalent be detectable, if neutron dose equivalent exceeds one-third of photon dose equivalent, and that the dosemeters have good performance in such fields(11,12).

Albedo TLD

The mixed field detection capability was evaluated by irradiating eight groups of albedo TLDs (four TLDs per group) to two neutron dose equivalent levels (0.5 mSv and 1.5 mSv) with four H_n/H_γ (3:1, 1:1, 1:3, and 1:10) using both the ^{238}Pu–Be and ^{137}Cs sources.

Pure field exposures of 1 mSv were also made. For the neutron exposure the ^{238}Pu–Be source was used whereas ^{137}Cs was used for the gamma exposure.

The precision, bias, and accuracy values of the neutron and gamma dose equivalent readings in these mixed neutron–gamma fields are shown in Tables 1 to 3, respectively. Precision is expressed in 1σ (in %) of the mean reading, which was computed from the four TLDs per exposure group. Bias is expressed as the percentage difference between the mean value of a group in the mixed field and the true value. Since the true values were not known, the mean values in the pure field irradiations were used as reference values and were assumed to be the true values in the mixed fields. Therefore, the mean value in a pure field has a bias of zero (see Table 2). If the mean value is smaller than the true value, the bias is negative. Accuracy is defined to be the sum of the absolute value of the bias and precision.

The neutron dose equivalent (H_n) estimates were made by both readings A and T. The photon dose equivalent (H_γ) estimates are generally made by using an additional photon dosemeter. However, the photon dose equivalent estimates were made here by using the TLD-700 elements (Cd-covered TLD-700 is called A1 and the other TLD-700 is called T1). The small gamma component (~ 4.3%) of the ^{238}Pu–Be source was not included in the total photon dose equivalent. Consequently, for the photon dose equivalent estimates, the reading of TLD-700 in a mixed field irradiation was corrected with the reference value of the TLD-700 reading from the pure ^{238}Pu–Be irradiation results.

Table 1 shows that the gamma precisions in all mixed fields were within 3.5%. The precision in the field with a H_n/H_γ = 3:1 and H_γ = 0.167 mSv was the lowest. Note that this 3.5% precision value might be partly due to the very low H_γ irradiation (only 0.167 mSv). The precision for the pure gamma field was about 1%. The excellent gamma precision results indicate the successful use of the ECC method to correct the individual sensitivity difference of the TLD elements. The gamma bias values were all

Table 1. Precision of neutron and gamma dose equivalent reading of the Harshaw albedo TLD in mixed neutron–gamma fields.

n/γ	H_n (mSv)	Neutron (%) A	Neutron (%) T	H_γ (mSv)	Gamma (%) A1	Gamma (%) T1
3/1	0.5	5.5	3.0	0.167	3.5	3.4
1/1	0.5	2.4	1.8	0.5	1.0	0.6
1/3	0.5	3.4	1.4	1.5	0.7	0.9
1/10	0.5	24.4	7.8	5.0	1.2	0.4
3/1	1.5	6.4	0.9	0.5	0.7	0.5
1/1	1.5	6.0	2.2	1.5	1.1	0.5
1/3	1.5	7.4	2.7	4.5	0.9	0.7
1/10	1.5	19.2	19.6	15.0	1.2	0.4
Pure H_n	1.0	2.3	1.9	0	–	–
Pure H_γ	0	–	–	1.0	1.1	0.8

1. Percentage is one standard deviation value computed from 4 TLDs per group.
2. A and T refer to the neutron readings of the Cd-covered TLD-600 and the other TLD-600 element, respectively.
3. A1 and T1 refer to the gamma readings of the Cd-covered TLD-700 and the other TLD-700 element, respectively.

Table 2. Bias of neutron and gamma dose equivalent reading of the Harshaw albedo TLD in mixed neutron–gamma fields.

H_n/H_γ	H_n (mSv)	Neutron (%) A	Neutron (%) T	H_γ (mSv)	Gamma (%) A1	Gamma (%) T1
3/1	0.5	– 2.3	0.2	0.167	−0.9	−3.5
1/1	0.5	2.3	0.9	0.5	0.7	−1.1
1/3	0.5	7.9	5.1	1.5	0.9	0.6
1/10	0.5	8.4	6.9	5.0	3.2	1.4
3/1	1.5	– 0.2	−1.4	0.5	−1.7	−4.2
1/1	1.5	0.1	−0.2	1.5	1.5	−0.2
1/3	1.5	0.5	−2.8	4.5	2.8	2.2
1/10	1.5	−13.4	−1.2	15.0	4.0	2.4
Pure H_n	1.0	0	0	0	–	–
Pure H_γ	0	–	–	1.0	0	0

1. The bias percentage is the difference between the mean value in each mixed field and the reference value in pure field, assuming the latter is the true value. (i.e. bias = 0).
2. See Table 1 for the meanings of A, T, A1, and T1.

Table 3. Accuracy of neutron and gamma dose equivalent reading of the Harshaw albedo TLD in mixed neutron–gamma fields.

H_n (mSv)	H_n/H_γ	Neutron (%) A	Neutron (%) T	Gamma (%) A1	Gamma (%) T1	H_t (mSv)	Error of H_t (%) A & A1	Error of H_t (%) T & T1
0.5	3/1	7.8	3.2	4.4	6.9	0.667	7.0	4.1
0.5	1/1	4.7	2.7	1.7	1.7	1.0	3.2	2.2
0.5	1/3	11.3	6.5	1.6	1.5	2.0	4.0	2.8
0.5	1/10	32.8	14.7	4.4	1.8	5.5	7.0	3.0
1.5	3/1	6.6	2.3	2.4	4.7	2.0	5.6	2.9
1.5	1/1	6.1	2.4	2.6	0.7	3.0	4.4	1.6
1.5	1/3	7.9	5.5	3.7	2.9	6.0	4.8	3.6
1.5	1/10	32.6	20.8	5.2	2.8	16.5	7.7	4.4

1. Accuracy is the sum of absolute value of bias and precision.
2. H_t is the total dose equivalent (neutron + gamma), not including the gammas from neutron source. See text for error estimate.
3. See Table 1 for the meanings of A, T, A1, and T1.

within 4% (Table 2). The gamma accuracies were all within about 5%, except in the field with the lowest H_γ (Table 3). The good gamma dose detection performance in mixed neutron–gamma fields can be attributed to the following causes: (a) TLD-700 is nearly insensitive to neutrons, (b) the use of ECC, and (c) good short-term stability of the photomultiplier tubes (PMTs) 2 and 3, which read the two TLD-700 elements.

Table 1 shows the neutron precision ranges from 2.4% to 24.4% for reading A and 0.9% to 19.6% for reading T, with the lowest precision in the fields with H_n/H_γ = 1:10. The precision attained in the pure ^{238}Pu–Be field was 2.3% and 1.9% for readings A and T, respectively. The precision of reading A was slightly worse than that of reading T, because the short-term stability of PMT 1 which read the Cd-covered TLD-600 element was slightly worse than that of PMT 4 which read the other TLD-600 element. The neutron reading had worse precision than the gamma reading. This was due to (a) an additional photon signal subtraction step being needed to obtain the neutron signal, and (b) the higher instability of the TLD-600 signal due to its narrower region of interest of TL signal$^{(4)}$. Table 2 shows that the neutron bias is larger when H_n/H_γ is lower. Neutron bias was highest in the field with a H_n/H_γ = 1:10.

Table 3 shows the expected results for the accuracy of the neutron dose equivalent measurements in mixed neutron–gamma fields: the lower the H_n/H_γ, the lower the neutron accuracy in a mixed field. The worst neutron accuracy was about 33% for reading A and 21% for reading T in the fields with H_n/H_γ = 1:10. The neutron accuracy ranged from 2.3% to 11.3% for the other mixed fields (H_n/H_γ from 3:1 to 1:3). These results indicate the good neutron dose equivalent detection performance of the albedo TLD in mixed fields. The good neutron detection capability in mixed fields can also be attributed to the use of both the ECC and RCF corrections.

Although the neutron accuracy in the field with a H_n/H_γ = 1:10 was about 33%, the accuracy of the gamma dose equivalent (which is 10 times higher than the neutron dose equivalent) estimate was good. Therefore, the total dose equivalent (H_t, neutron + gamma) estimate was still very good. The accuracy of the H_t estimate was derived by the equation: $(A_n H_n + A_\gamma H_\gamma)/H_t$, where A_n and A_γ are the accuracy values of the neutron and gamma dose equivalent readings, respectively. Table 3 shows that the errors of the total dose equivalent estimates in all mixed fields are less than 8%.

Bubble detector

Two BD-100R and two BDS-1500 were exposed to 0.18 Sv of ^{137}Cs gammas and 0.2 Sv of ^{90}Sr–^{90}Y betas. No reading was observed from either irradiation. The results agree with those reported by Ipe and Busick$^{(9)}$.

ANGULAR DEPENDENCE

Albedo TLD

The angular response performance evaluation of the albedo TLD has been studied by following the DOELAP methodology$^{(11)}$. The detailed results are to be published in this journal. The conclusion from that study is that the albedo TLD has a bell shaped angular dependence for front incident angles. The relative responses at 30°, 60°, and 85° for irradiation by ^{252}Cf(D$_2$O) or ^{252}Cf were about 0.9, 0.6, and 0.2, respectively. The neutron sensitivities of the Cd-covered TLD-600 for ^{252}Cf(D$_2$O) and ^{252}Cf at perpendicular (0°) irradiation were 794 mR.mSv^{-1} and 83 mR.mSv^{-1}, respectively.

Bubble detector

Due to its cylindrical shape, the current BD has a 2π rotational angular independence and a small horizontal angular dependence for free-in-air exposures. For on-phantom exposure, the BD is less sensitive to reflected neutrons than to incident neutrons (unlike the albedo TLD), due to its energy threshold. For the same reason, the BDS-1500 which has a much higher threshold than BD-100R is less angular dependent than the BD-100R for on-phantom exposures. The response difference of the BD-100R exposed to ^{252}Cf(D$_2$O) was less than 5% between the incidence angles of 0° and 85° vertical and about 15% between 0° and 85° horizontal. Considering the statistical errors of the BD readings, the angular response of the BD for the on-phantom irradiation can be regarded as isotropic. Note that the angular dependence of the BD depends on the tube shape and the BD can be tailored easily to have other desired angular responses.

NEUTRON ENERGY DEPENDENCE

The energy dependence study for the albedo TLD and the BD was conducted by following the International Organization for Standardization draft recommendations$^{(13)}$. A total of eleven neutron energies from 2 keV to 14.8 MeV were used. Monoenergetic neutrons at eight energy points (0.1, 0.25, 0.565, 1.2, 2.6, 3.2, 5.0, and 14.8 MeV) from a Van de Graaff accelerator were provided at the Pacific Northwest Laboratories (PNL). Three filtered reactor beams (2, 24, and 144 keV) were provided at the National Institute of Standards and

Technology (NIST).

PNL irradiations

The irradiation characteristics of the monoeneregetic neutrons from PNL(14) are described in Table 4. The PNL 2 MV Van de Graaff accelerator room is about 8.5×8.5×6.1 m^3. The neutron producing target was located 3.2 m above the floor centre of a 6.1×6.1×2.1 m^3 pit which has an aluminium grid cover. All large neutron scattering objects were at least 2.4 m away from the target. A precision long counter was used to monitor the neutron fluence during the irradiation. The phantom was placed at a phantom-to-target distance of 50 cm, and an appropriate laboratory neutron emission angle. The distance and angle of the phantom were chosen to give acceptable uniformity of the radiation field at the dosemeters' position. Factors such as the accelerator's stability and the neutron output strength were also considered in selecting the projectile energy and neutron emission angle, so that neutrons of good quality could be produced.

The projectile beam energy was determined by the analysing magnet, which was calibrated by using the well known threshold energy of the ^{7}Li(p,n)^{7}Be reaction. The stated uncertainty in neutron energy is due to the finite width of the projectile energy and the projectile energy loss in the target. The neutron contamination estimate was made with a blank target and is an estimate of background and the contributions (if any) by competing reactions.

Four TLDs and one set of BDs (one BD-100R and one BDS-1500) were irradiated as a group for each energy. The BDS-1500 was not irradiated with neutrons below 1.2 MeV. The BD set was placed in the centre of the phantom and the four TLDs were placed at 90° interval around the outer edge (about 1 cm away) of the BDs. After an appropriate irradiation time, the BD set was replaced by a new set. Therefore, there were four TLDs, two BD-100R, and two BDS-1500 (except for neutrons below 1.2 MeV) irradiated for every energy. The fluences shown in Table 4 were for the albedo TLDs. The fluence for the BDs was less than half of the fluence for the TLDs. The fluence uncertainty was 10% for proton beam reactions and 15% for deuteron beam reactions. The ICRP 21 fluence-to-dose equivalent conversion factors (h_Φ) for these neutron energies(3,13) are also shown in Table 4. The temperature during irradiations was within 21°C–22°C.

NIST irradiations

The irradiation characteristics at NIST(15,16) are described in Table 5. The scandium filtered beam has 95.6% of the flux at 2 keV (full width half maximum (FWHM) is 35%), 1.3% at 39 keV, and the rest at other high energies. The iron-aluminium filtered beam has 97.1% of the flux at 24 keV (FWHM = 8.3%) and 2.9% at energies between 50 and 400 keV. The silicon filtered beam has 99.7% of the flux at 144 keV (FWHM = 17.4%) and 0.3% at 54 keV peak. Response corrections of the albedo TLD and the BD-100R for the contamination neutrons were made in the energy dependence study. Four TLDs and two BD-100R were exposed for each beam. Two BDS-1500 were exposed only to the 144 keV beams. Since the beam diameter was small (5 cm), the beam was scanned in a raster to cover a 25 cm square area centred on the phantom. The four TLDs were placed at 90° intervals around

Table 4. Characteristics of the monoenergetic neutron irradiations from the Van de Graaff accelerator at PNL(a).

Energy (keV)	Energy uncertainty (%)	Reaction	Projectile energy (MeV)	Lab. angle (deg.)	Fluence(b) (10^6 cm^{-2})	ICRP 21 h_Φ (10^{-10} Sv.cm^2)	Neutron contamination (%)
100(c)	12	T(p,n) ^{3}He	1.258	75	8.6	0.579	<1
250(c)	8.4	T(p,n) ^{3}He	1.252	45	4.4	1.18	<1
565(c)	4.8	T(p,n) ^{3}He	1.494	30	4.6	2.20	<1
1200(d)	4.6	^{12}C(d,n)^{13}N	1.588	30	2.9	3.52	<6
2600(e)	0.3	D(d,n) ^{3}He	0.584	90	2.5	4.06	<3
3200(e)	0.8	D(d,n) ^{3}He	0.824	60	2.5	4.10	<3
5000(e)	0.9	D(d,n) ^{3}He	1.830	15	5.0	4.08	<9
14800(f)	0.1	T(d,n) ^{4}He	0.754	75	4.9	4.18	<3

(a) Irradiation room of PNL is 8.5×8.5×6.1 m^3. Target is in room centre.
(b) Total fluence for TLD irradiation.
(c) Target is 0.235 mg.cm^{-2} T–Ti on Cu disc and fluence uncertainty is 10%.
(d) Target is 0.518 mg.cm^{-2} ^{12}C on Ta disc and fluence uncertainty is 15%.
(e) Target is 0.560 mg.cm^{-2} D–Ti on Cu disc and fluence uncertainty is 15%.
(f) Target is 0.235 mg.cm^{-2} T–Ti on Cu disc and fluence uncertainty is 15%.

Table 5. Characteristics of the filtered reactor beams at NIST.

Energy (keV)	Main filter[(a)] material	FWHM (%)	Contamination[(b)] keV (%)	Fluence[(c)] (cm^{-2})	ICRP 21 h_Φ (10^{-10}Sv.cm^2)
2	Sc	35.0	29, others (4.4)	4.9×10^7	0.0943
24	Fe–Al	8.3	>100 (2.9)	2.6×10^7	0.193
144	Si	17.4	54 (0.33)	1.3×10^7	0.773

(a) Secondary filter of Ti is added for the 2 and 144 keV beams to suppress the contamination peaks.
(b) See text for contamination description.
(c) Nominal beam fluence. Uncertainty is about 10 to 15%.

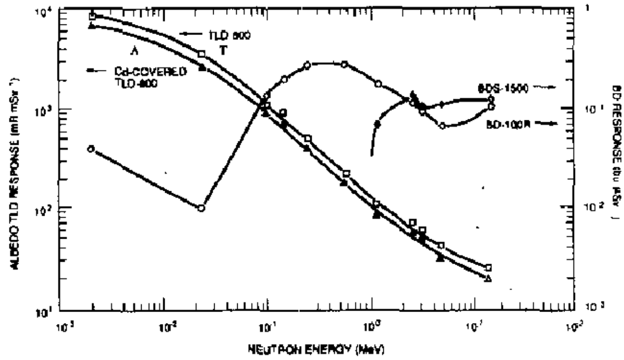

Figure 6. Neutron energy dependence of the Harshaw albedo TLD and bubble detectors, determined with on-phantom irradiations from monoenergetic neutrons.

the inner edge of a 15×15 cm^2 square. The BDs were placed in the phantom centre. The fluence uncertainty was about 10% to 15%. Control dosemeter measurements outside the beam were made to estimate the scattering background. The temperature during all irradiations was within 21°C–22°C.

Energy dependence results

The energy dependence of the dose equivalent responses for the albedo TLD, BD-100R, and BDS-1500 are plotted in Figure 6. These response functions are given for the bubble detectors having a sensitivity of 0.1 bubble per μSv to BTI's ^{238}Pu-Be source. This source is used at BTI to determine the nominal sensitivities and for the quality assurance of the BDs.

If the energy dependence curves in Figure 6 were replotted in fluence responses, it can be seen that the BD-100R and BDS-1500 function more like a 'fluence dosemeter' (i.e. fluence response is energy independent) than a 'rem dosemeter' (i.e. dose equivalent response is energy independent). The BD-100R energy dependence is similar to that of BD-100[(17,18)]. The albedo TLD results also agree well with the expected results[(19)].

SUMMARY AND CONCLUSIONS

The Harshaw albedo TLD and the bubble detctors (BD-100R and BDS-1500) have been characterised in detail and the results are summarised as follows:

1. *Re-usability*. The albedo TLD and the BD are re-usable and the sensitivity variations (1σ) during re-use are <5%[(4)] and ~15–20%, respectively. Reader anneal and a 3 month exchange period are satisfactory for TLD usage[(4)]. Recompression at least weekly and periodic sensitivity checks are recommended for the BD usage.
2. *Linearity*. The Albedo TLD has a linear neutron dose equivalent response range of at least 2 orders of magnitude. The linear range of the BD is up to at least 100 bubbles.
3. *LLD*. The LLD of the albedo TLD is ~92 μSv for ^{252}Cf and ~10 μSv or ^{252}Cf(D_2O). The LLD for the BD is no greater than 10 μSv for neutrons with energies higher than its threshold for a weekly re-use procedure.
4. *Mixed field detection capability*. In the field with a H_n/H_γ greater than 1:3, the accuracy of neutron dose equivalent measurement of the albedo TLD is better than 12%. In all mixed fields tested, the accuracies of total dose equivalent estimates are better than 10%. The BD has no response to photons and betas with energies less than 6 MeV.
5. *Angular dependence*. For front incidence, the albedo TLD and BD have a bell shaped and isotropic angular response, respectively.
6. *Energy dependence*. The albedo response is high at low energies (< 1 keV) and starts to fall at high energies (> 10 keV). The responses of the albedo TLD for ^{252}Cf(D_2O) and ^{252}Cf differ by a factor of ten (794/83). The fluence response of the BD is roughly flat for neutrons above its threshold.

The characterisation results demonstrate that the albedo TLD and the two BDs have good dosimetric properties and they can complement each other. Therefore, a combination dosemeter (i.e. the CPND) consisting of the Harshaw albedo TLD and the two BDs would be a promising neutron dosemeter. A 4-interval spectral unfolding algorithm has also been developed for the CPND, based on the energy dependence study results. The performance (spectrometry and low dose equivalent measurement capability) of the CPND has been evaluated rigorously. A companion paper describing the performance evaluation of the CPND is to be published.

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APPENDIX

RE-USABILITY STUDY OF THE BUBBLE DETECTORS

From the operational point of view, it is desired that the BD can be used for a long time without many recompressions being required. It is known qualitatively that the less frequently the BD is recompressed, the less it can be re-used. The manufacturer stated that the BD-100R can be used for one month without recompression and that it can be re-used for three months if recompressed daily. No re-usability of the BDS-1500 has been reported yet.

Phase I study

Nine BDS-1500 (sensitivities between 0.16–0.55 bu.μSv^{-1}) and nine BD-100R (low sensitivity 0.056 bu.μSv^{-1}) bubble detectors from the first purchase batch were tested for re-usability by tracing their individual sensitivity. To optimise the re-use procedure, these nine BD-100R and nine BDS-1500 were divided into four groups for testing four different re-use procedures. Three BD-100R and three BDS-1500 were recompressed on the second day after irradiation with the personal recompression device for 0.5 h. Three other groups (2 BD-100R and 2 BDS-1500 in each group) were recompressed with the recompression chamber using (a) second day recompression, (b) weekly recompression (exposed Monday and recompressed Friday), and (c) bi-weekly recompression procedures, respectively. The personal recompression device can exert about 5 MPa (725 psi) hydraulic pressure. The recompression chamber can produce hydraulic pressure up to 6.9 MPa, but only 2.8 MPa was used in this study.

The detectors were exposed in reproducible positions to the ^{238}Pu–Be neutron source in the neutron room. The dose equivalents delivered to the BDs were varied, so that the BDs with different sensitivities can have similar reading (i.e. number of bubbles). The temperature was between 20°C and 24°C and no response correction for temperature dependence was made. The stability of BD is expressed in terms of one standard deviation (i.e. 1σ in %) of the bubble readings over the re-use period.

BDS-1500 re-usability

The six month re-usability study results of the BDS-1500 using the second day recompression and weekly recompression procedures with the recompression chamber (2.8 MPa, 1 h) are shown in Figures A1 and A2, respectively. There were 52 re-uses and 24 re-uses over the 6 month period for the second day recompression and weekly recompression procedures, respectively. The stability

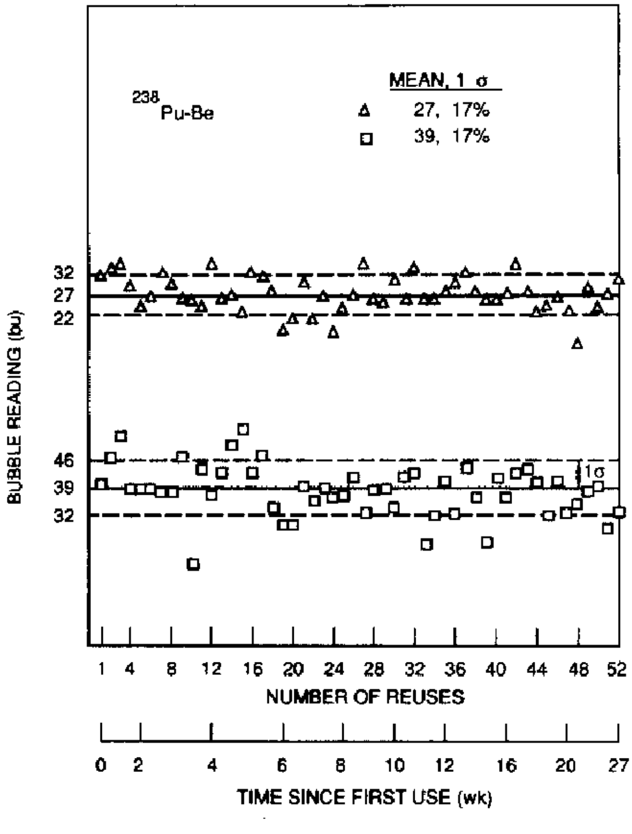

Figure A1. Re-usability of BDS-1500 using the second day recompression procedure with the recompression chamber (2.8 MPa, 1h).

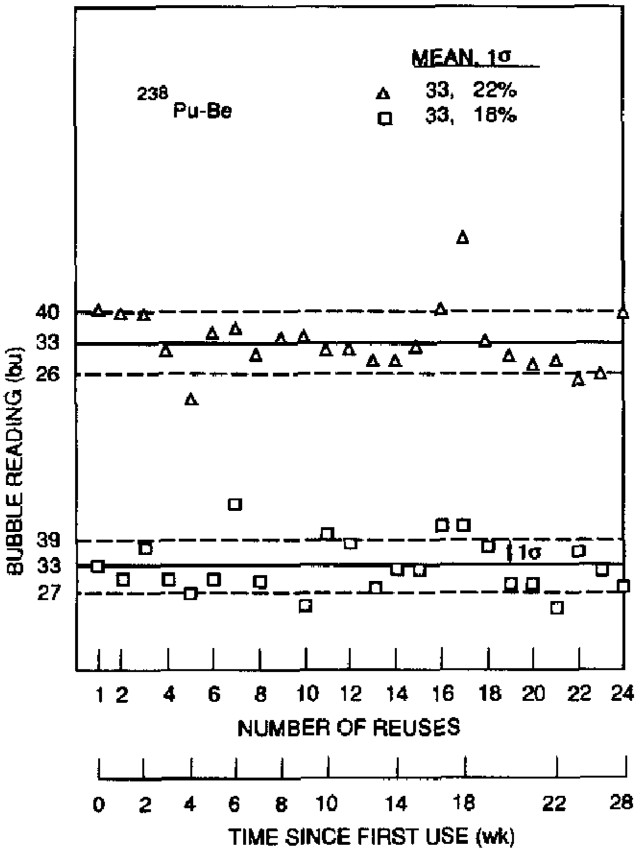

Figure A2. Re-usability of BDS-1500 using the weekly recompression procedure with the recompression chamber (2.8 MPa, 1 h).

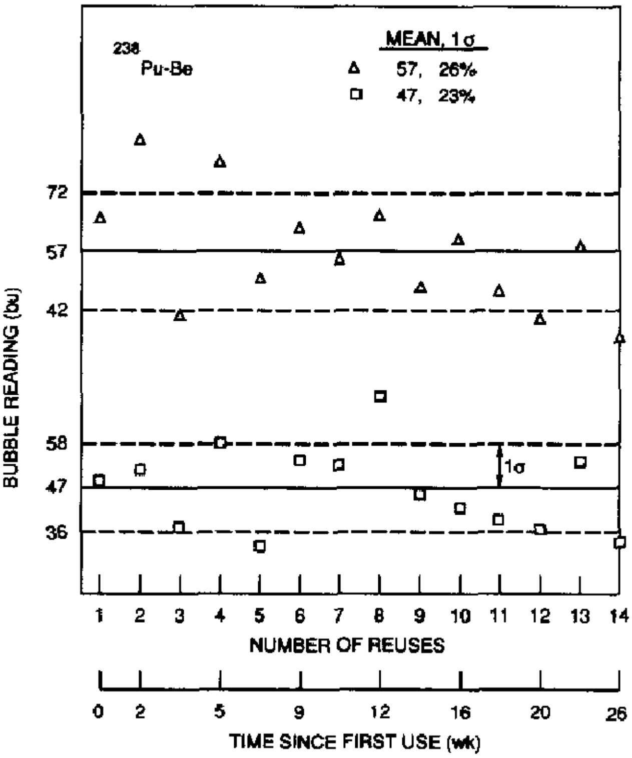

Figure A3. Re-usability of BDS-1500 using the biweekly recompression procedure with the recompression chamber (2.8 MPa, 2h).

results for both the second day recompression and weekly recompression procedures were similar over the first quarter (1σ ~ 17%). Over the 6 month re-use period, the second day recompression procedure had slightly better stability (1σ ~ 17%) than the weekly recompression procedure (1σ ~ 18–22%).

The 6 month (14 re-uses) re-usability results of the BDS-1500 using the bi-weekly recompression procedure (2.8 MPa, 2 h) are shown in Figure A3. The bi-weekly recompression procedure resulted in the poorest re-usability performance (highest 1σ value ~ 23–26%). A few abnormal non-spherical bubbles, an indication of polymer deterioration, also formed one month after initial neutron exposure using the bi-weekly recompression procedure.

The re-usability of the BDS-1500 using the second day recompression procedure with the personal recompression device (higher recompression pressure and shorter recompression time) were similar to the one using the recompression chamber. The 1σ value was ~18% for the first three months (36 re-uses) and was ~20% over the 5 month period (42 re-uses).

BD-100R re-usability

The BD-100R from the first batch in all four recompression procedure studies had the same poor re-usability performance. About two weeks after sensitisation, the sensitivity dropped gradually to about a tenth of the original, and then maintained that sensitivity level. The results were much worse than other reported results$^{(5-7)}$.

The BD-100R (sensitivity 0.7 bu.μSv^{-1}) was shown$^{(5)}$ to be re-usable up to 24 times in 48 days with the mean response variation of the BD-100R batch less than 15% using a second day recompression procedure (6.2 MPa, 1 h). Toronto General Hospital personnel$^{(6)}$ re-used the BD-100R (sensitivity 0.56 bu.μSv^{-1}) for 3 months using a daily recompression procedure (2.8 MPa, 15 h) and no drop of sensitivity was experienced. Reilly and Nelson$^{(7)}$ re-used the BD-100R (sensitivities between 0.39–0.47 bu.μSv^{-1}) 21 times and observed that the response variation over re-use was totally statistical.

The BD-100R sensitivity loss problem in phase I study was partly due to the difficult production control of the low sensitivity BD-100R (only 0.056 bu.µSv^{-1}, about a tenth of the BD-100R used by others). An over-long storage period on the vendor's shelf could be another reason. Some superheated droplets may diffuse out of the polymer due to the deterioration of polymer.

Phase II study

Four BDS-1500 (sensitivities between 0.1–0.5 bu.µSv^{-1}) and five BD-100R (sensitivities between 0.085–0.82 bu.µSv^{-1}) from the second purchase batch were tested. A 3 month (20 re-uses) study was conducted using only the second day recompression procedure.

The re-usability results of the BDS-1500 in the Phase II study were similar to those in the Phase I study with 1σ of ~21%.

The re-usability results of the BD-100R are shown in Figure A4. The 1σ values ranged from 15% to 33%. The response of the BD-100R with the lowest sensitivity (0.085 bu.µSv^{-1}) decreased and 1σ was 33%. The large 1σ (33%) for the BD-100R with the sensitivity of 0.15 bu.µSv^{-1} was due to the first two high data points which might have resulted from statistical variations. The BD-100R bubble detectors with sensitivities in normal production range (0.1–1 bu.µSv^{-1}) had no significant sensitivity loss problem as the low sensitivity BD-100R in the Phase I study.

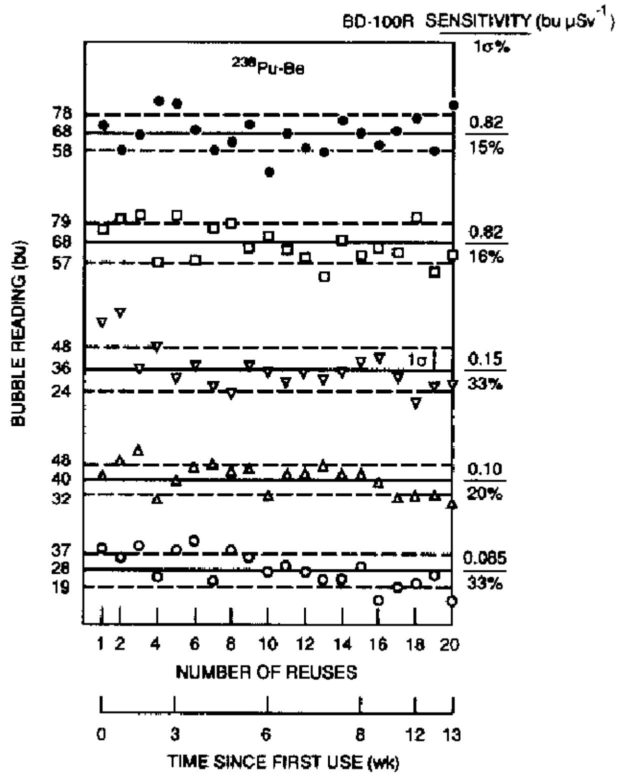

Figure A4. Re-usability of BD-100R (sensitivity in normal production range) using the second day recompression procedure with the recompression chamber.

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