Operational Topic

Bubble dosimeters have been evaluated for daily use to measure personnel neutron doses and the results obtained have been compared to those measured with albedo TLDs.

Operational Comparison of Bubble Dosimetry with Albedo Thermoluminescent Dosimetry for a Selected Group of ^{238}Pu Workers

Leonard L. Romero, Jeffrey M. Hoffman,* Elizabeth M. Foltyn,† and Thomas E. Buhl**

Abstract: *Personnel neutron dosimetry continues to be a difficult science due to the lack of availability of robust passive dosimeters that exhibit tissue equivalent, or near tissue equivalent response. The dosimeter most used for neutron dosimetry in the United States remains the albedo thermoluminescent dosimeter (TLD). Track-etch and bubble dosimeters generally have a more favorable energy response than albedo dosimeters but are more difficult and expensive to use. This paper is an operational study that compares the use of albedo TLDs with bubble dosimeters to determine whether bubble dosimeters do provide a useful daily tool to achieve as low as reasonably achievable (ALARA) goals that can yield measurements close to the dose-of-record from TLD. A group of workers working on the radioisotope thermoelectric generators (RTGs) for the National Aeronautics Space Administration (NASA) Cassini space mission wore both bubble dosimeters and albedo dosimeters over a period from 1993 through 1996. The bubble dosimeters were issued and read on a daily basis and the data were used as an ALARA tool. The personnel albedo dosimeter was processed on a monthly basis and used as the dose-of-record. The results of this study indicated that cumulative bubble dosimetry results agreed with whole-body albedo dosimetry results within about 37%. However, it was observed that there is a significant variability of the results on an individual basis both month-to-month and from one individual to another.*

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Key words: *^{238}Pu; dosimetry; thermoluminescent dosimetry; safety standards*

Los Alamos National Laboratory (LANL) is a large multidisciplinary research institution that utilizes a wide variety of radioactive materials and radiation-producing machines in the pursuit of its research and development mission. Neutron radiation is a major portion of the Laboratory's collective dose, accounting for about 75% of the approximately 200 person-rem incurred each year. The sources of neutron radiation range from highly moderated sources around critical assemblies, such as those found at technical area (TA) 18 and in the plutonium facility (TA-55), to very high energy neutrons (up to 800 MeV), which are accelerator produced at the Los Alamos Neutron Science Center (TA-53). Included in the operations at TA-55 is the production of RTGs for power sources for NASA. These power sources are made of ^{238}Pu. The associated neutron spectra vary during the production operations but yield maximum neutron energy of about 5 MeV. Typical feed is enriched in the ^{238}Pu isotope to approximately 80%, with approximately 15% ^{239}Pu and the remainder plutonium isotopes, ^{240}Pu, ^{241}Pu, and ^{242}Pu. Characterization and processing steps include calorimetry and analysis of incoming feed, ^{16}O exchange, ball-milling, slugging and screening, granule seasoning, hot pressing, post sintering, encapsulation, nondestructive testing, and preparation for shipment (Kent 1979).

The increased plutonium-processing activity throughput

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beginning in 1993 as a result of the NASA Cassini mission resulted in higher occupational neutron doses, making worthwhile added monitoring efforts for purposes of achieving ALARA. Workers wore supplemental bubble dosimeters, in addition to routine whole-body TLDs, and exchanged them on a daily basis for monitoring neutron doses from 1993 through 1996. The whole-body TLD has been and remains used as the dose-of-record.

This study focuses on the neutron dosimetry needs of the Actinides Ceramics Group at TA-55 who process plutonium oxide into heat sources for terrestrial and space applications. Specifically, daily bubble dosimeter results are compared to whole-body TLD neutron results for the LANL ^{238}Pu operations from 1993 through 1996. Neither bubble dosimeters nor albedo TLDs are perfect dose-equivalent-reading dosimeters, and the advantages and limitations of each type are discussed in this work.

MATERIALS AND METHODS

Early whole-body neutron TLD use at LANL (since 1980)

LANL utilized a Harshaw/ Bicron‡ Model BGN-7776 whole-body TLD for performing routine external radiation dosimetry. This dosimeter was regularly tested and approved for use by the Department of Energy Laboratory Accreditation Program (DOELAP) for external dosimetry systems. The dosimeter is made up of four TLD elements placed behind different filter materials and thicknesses. The first three TLD elements are lithium fluoride (doped with Mg and Ti) enriched in Lithium-7 (Harshaw/ Bicron Model TLD-700); the fourth TLD element is lithium fluoride (doped with Mg and Ti) enriched in Lithium-6 (Harshaw/ Bicron Model TLD-600). Lithium-6 has a thermal neutron absorption cross section of about 942 barns (and exhibits a $1/v$ energy dependence); Lithium-7 has a negligible neutron cross section. The Model BGN-7776 whole-body dosimeter and associated elements and filtration are shown in Fig. 1.

The albedo neutron dosimeter is located in positions three and four of the Model BGN-7776 dosimeter with the paired TLD-600 and TLD-700 elements under identical plastic filtration. The TLD-600 and TLD-700 dosimeter materials exhibit equivalent photon response; TLD-600 is also sensitive to thermal neutrons and TLD-700 is insensitive to them. Plastic filtration is used as a non-neutron absorbing mechanical media that is identical for both elements. This is actually a quasi-albedo dosimeter since there is not a thermal neutron-absorbing filter over the top of this TLD element pair. Therefore, the TLD-600 in the LANL Model BGN-7776 dosimeter will respond to both incident thermal neutrons as well as albedo neutrons (which are thermal neutrons produced from higher energy neutrons moderated to thermal energies and reflected from the body).

Because the quasi-albedo dosimeter only responds to incident and reflected thermal neutrons, this dosimeter exhibits a highly energy dependent response relative to that for dose deposition in the human body. The LANL Model BGN-7776 albedo dosimeter relies on the use of neutron correction

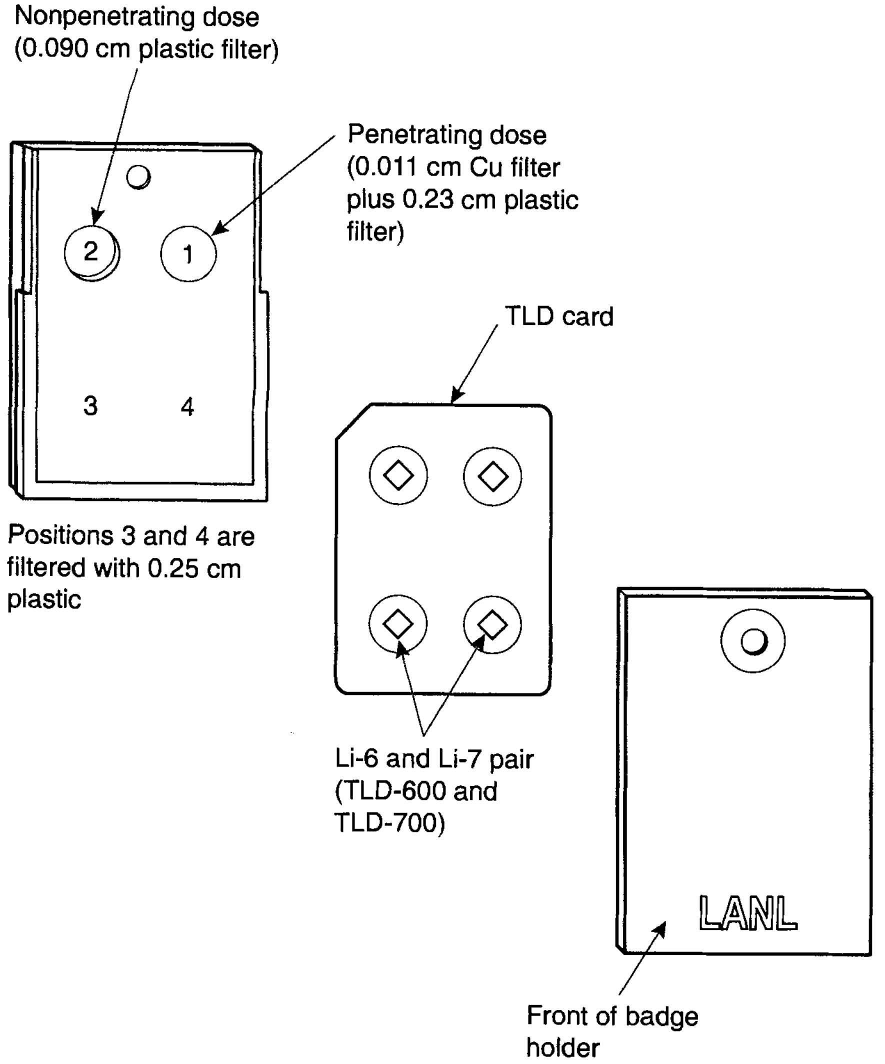

Figure 1. LANL Model BGN-7776 whole-body dosimeter.

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‡ *Harshaw/Bicron-NE Corporation, 6801 Cochran Road, Solon, OH.*

factors (NCFs) to modify its energy-dependent response to estimate neutron dose in tissue.

Neutron correction factors for the albedo neutron dosimeter

All four TLD elements are equally sensitive to photon radiation and are, therefore, calibrated with ^{137}Cs using automated Harshaw/Bicron Model 6610C TLD calibrators. The gamma calibration of the neutron sensitive element, TLD-600 in position 4, must be modified to estimate neutron dose with the use of location-specific neutron correction factors. NCFs are multipliers that convert the gamma-equivalent nanocoulomb TLD output to true neutron dose for a given neutron spectrum. Location-specific factors are required because the neutron spectra can vary significantly for various locations within a given facility. NCFs for the LANL Model BGN-7776 albedo dosimeter can easily vary by more than an order of magnitude (less than 0.1 to greater than 1.0) for neutron sources and geometries encountered at the laboratory. NCFs for very highly moderated neutron sources at TA-55 have been measured to be less than 0.1 while NCFs for bare isotopic sources such as PuBe are on the order of greater than 1.3 (Casson et al. 1995). NCFs at LANL from 1980 until late 1995 were static factors assigned to an employee based on work location. Each employee had only one factor that was based on job location, and an employee's NCF was changed typically only when the employee's job changed or NCFs were updated for the area where the employee worked. Beginning in late 1995, a new whole-body dosimeter, called the Model 8823 dosimeter, was introduced, which allowed for the on-board calculation of an integrated NCF to be applied to the existing albedo dosimeter. This will be discussed in more detail later.

The primary method for determining NCFs from 1980 to 1995 at LANL was by the use of an §Eberline 9-inch NRD "rem-meter," a 40 × 40 × 15-cm Lucite phantom, a cart, and a set of Model BGN-7776 dosimeters. Fig. 2 shows the instrument configuration that was used for determining location-specific NCFs. The 9-inch NRD was operated in the integrating mode and the reading of this instrument, although itself not completely tissue-equivalent because it exhibits a significant over-response particularly in the several-hundred-keV region, was, nevertheless, assumed to be the true value.

The readings on the set of Model BGN-7776 dosimeters on-phantom near to the 9-inch NRD were averaged, and the NCF for each location was taken to be the quotient of the 9-inch NRD result to the average of the Model BGN-7776 dosimeter results.

One major failing of static NCFs lies in the fact that employees do not remain at one work location nor do the work processes remain constant. For this reason, NCFs have traditionally been conservatively assigned at LANL. This fact has been reported in several LANL publications (Casson et al. 1995; Harvey et al. 1993; Hoffman et al. 1992).

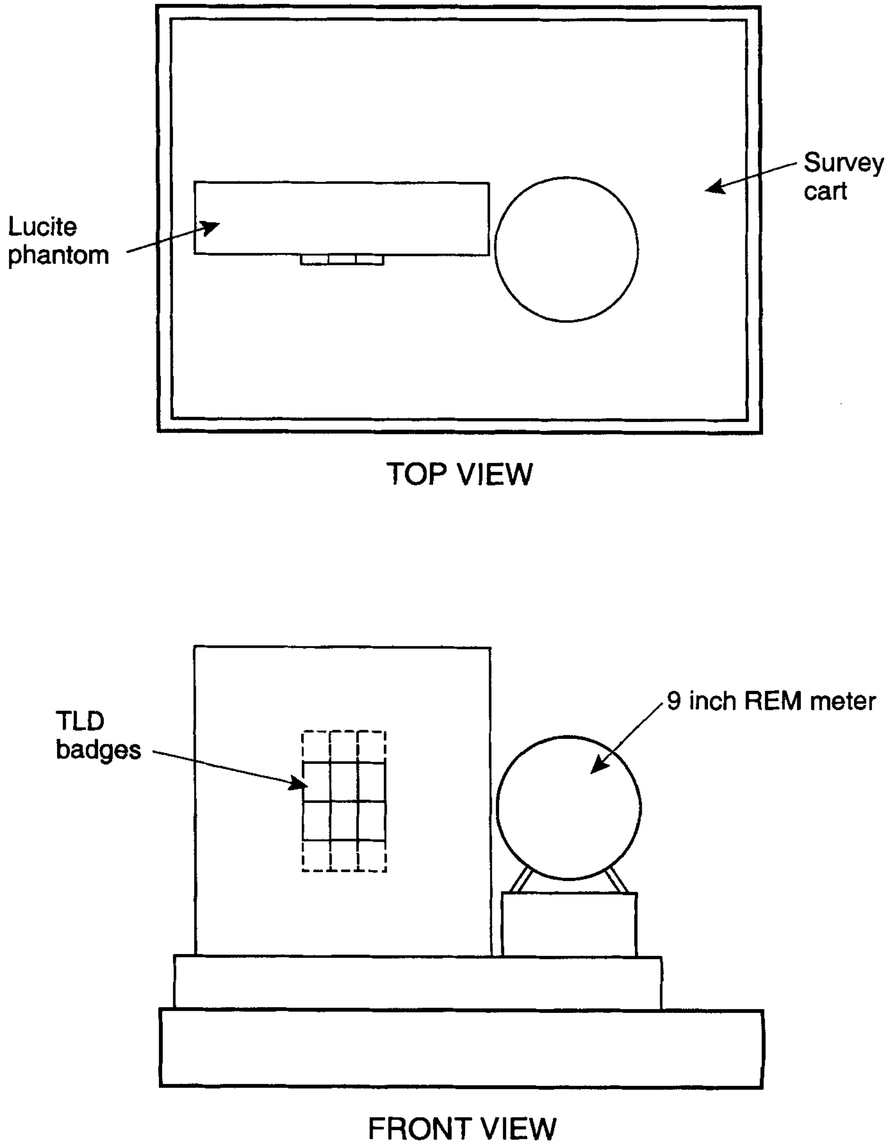

Figure 2. Instrument configuration for neutron correction factor measurements.

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Contemporary neutron dosimetry

The Model 8823 whole-body dosimeter is an improved design that in 1998 fully replaced the Model BGN-7776 dosimeter for the dose-of-record at LANL. LANL began using the Model 8823 dosimeter in late 1995 in combination with the standard Model BGN-7776 dosimeter strictly for the purpose of determining NCFs. The Model 8823 dosimeter has the capability to calculate an integrated NCF and has for the most part replaced the use of static NCFs at TA-55.

The Model 8823 dosimeter contains two TLD cards—one for beta and photon dosimetry and the other for neutron dosimetry. The neutron TLD card contains two pairs of TLD-600, −700 elements. One pair is fully surrounded by cadmium except there is an open area covered only by plastic toward the body in the classic Hankins||-type albedo dosimeter design. The other pair is fully surrounded by cadmium except there is an open area covered only by plastic facing away from the body (called an anti-albedo). Fig. 3 shows the holder of the Model 8823 dosimeter where the pairs of TLD-600, -700 elements are placed in positions 5 and 6 for the anti-albedo dosimeter and positions 7 and 8 for the albedo dosimeter. An empirically derived function exists to calculate an integrated NCF using the net-neutron responses of the albedo and anti-albedo elements in the Model 8823 dosimeter. The gamma signal is subtracted from the TLD-600 readings in positions 5 and 8 using the corresponding TLD-700 readings in positions 6 and 7 to yield net-neutron responses for the albedo and anti-albedo dosimeters. The ratio of the albedo to anti-albedo net neutron results yields an indication of the appropriate NCF to be applied. This calculated NCF was applied to the readings on the corresponding Model BGN-7776 dosimeter (Casson et al. 1995a).

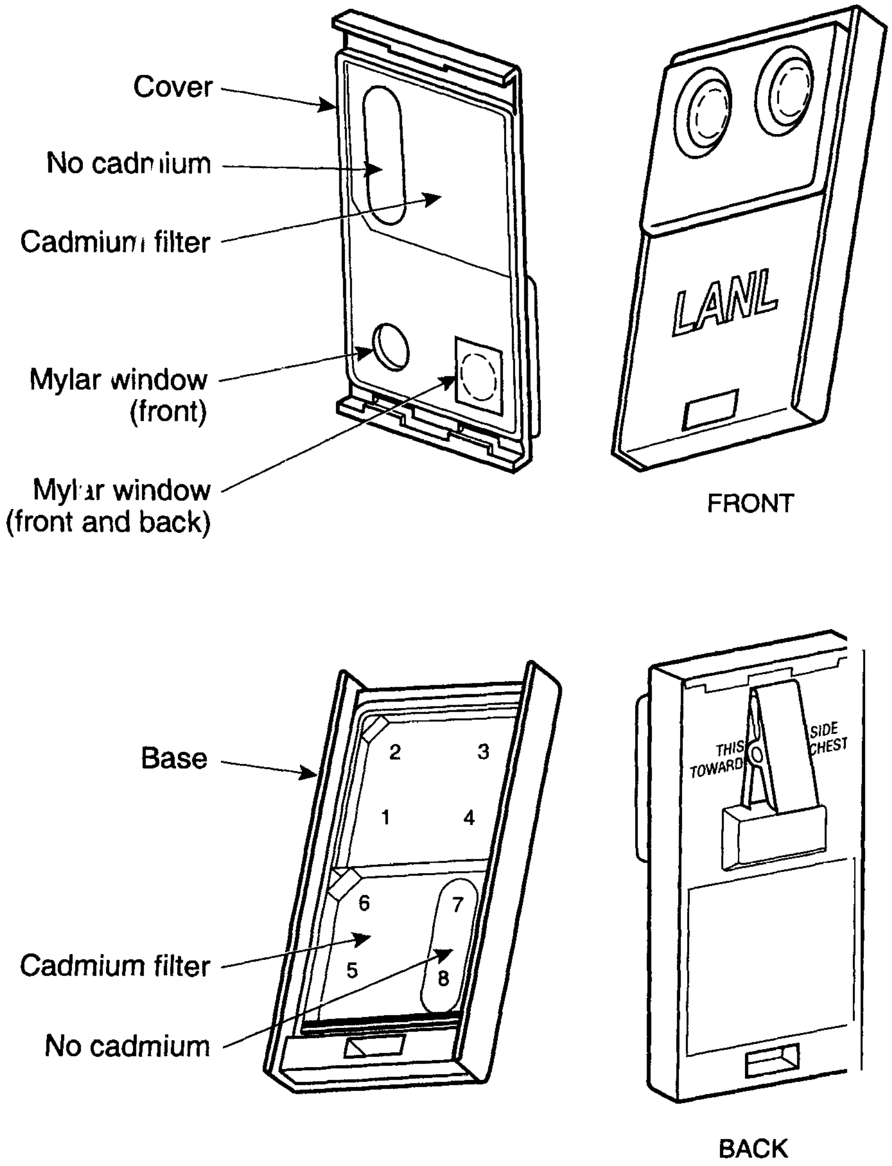

Figure 3. Model 8823 whole-body TLD showing placement of the cadmium filter with open window over positions 5 and 6 and under positions 7 and 8.

Bubble dosimetry

Commercial suppliers of neutron dosimeters that use superheated drop technology include Bubble Technology Industries¶ (BTI) and Apfel Enterprises, Inc.# LANL chose to use BTI as the supplier for bubble neutron dosimeters during this study period (1993–1996). Both BD-100R and BD-PND dosimeters were studied because BD-100R dosimeters were initially used at LANL but were eventually replaced with BD-PND dosimeters during the period of operations. The BD-100R requires temperature correction while the BD-PND is automatically temperature compensated over a limited range. For this reason, this paper focuses on this unique technology as it is applied by BTI but neither the authors (nor LANL) endorse or reject the products of either manufacturer of superheated drop dosimeters.

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¶ *Bubble Technology Industries, HWY 17, Chalk River, Ontario, Canada, KOJ 1JO.*

Apfel Enterprises, 25 Science Park, New Haven, CT, 06511.

The BTI bubble dosimeter is a passive, reusable, neutron dosimeter that allows instant visible detection of neutron radiation. It is lightweight and compact so that it can be worn on a lab coat or an area of limited space and hence is useful for personal monitoring. The dosimeter is unresponsive to gamma radiation and consists of droplets of superheated liquid dispersed in a transparent elastic polymer. When ionization occurs in the vicinity of these droplets, small bubbles form that remain in the polymer and provide an immediate visual record of the dose. The number of bubbles is proportional to the neutron dose over a wide neutron range (~200 keV−several MeV). The detectors have an isotropic response so neutron doses are recorded accurately regardless of the neutron direction relative to the detector. Bubble dosimeters have been used in diverse applications associated with the measurement of neutron radiation exposure to airline crews (Lewis et al. 1994), the measurement of neutron fields inside satellites in outer space (Ing et al. 1996) and are used as the legal dose-of-record for neutron exposures in some European countries.

The BD-PND and BD-100R bubble dosimeters were read on the BTI BDR-Series II evaluation system. This reading system uses light illumination of the bubble dosimeter tube that is captured on a camera. The image is transferred to a personal computer where automated analysis allows discrimination for acceptable bubbles based on size and shape. The evaluation system was configured according to the instructions in the user's manual. All bubble dosimeters were calibrated on a 40 × 40 × 15-cm Lucite phantom at 50 cm from a bare ^{252}Cf source to about 20 mrem. The level of 20 mrem was chosen as the calibration value because this level was high enough that it could be accurately delivered in the LANL calibration facility but low enough so that it would not saturate the bubble dosimeters. Bubble dosimeters could not be accurately processed in the reading system beyond about 600 bubbles due to image saturation. Typical BTI bubble dosimeters ranged in sensitivity from 1.2 to 22 bubbles per mrem.

Each time the bubble dosimeter is processed at LANL in the BDR-Series II evaluation system, it is read three times with a partial rotation of about 120 degrees of the dosimeter between readings. The results of the three readings yield an average bubble count. This bubble count is divided by the individual sensitivity correction factor that was determined during calibration, and then a temperature correction is applied for the BD-100R dosimeters to yield the neutron dose in mrem. BD-PND dosimeters require no temperature correction for normal workplace conditions. The calibration that was applied to all bubble dosimetry data produced at LANL was based only on the LANL calibration.

RESULTS AND DISCUSSION

Deviation of relative sensitivity with dose for bubble dosimeters

Since the bubble dosimeters used at LANL were for field operational use, the dosimeters were expected to be exposed over a range of 0 to 25 mrem per day. A study was performed to examine (1) the deviation in relative sensitivity of the bubble dosimeters over the anticipated occupational dose range for the various sensitivities of bubble dosimeters by usage level and (2) the effect of reading the dosimeter on two different readers located at different locations. The dosimeters evaluated were routinely being used at TA-55. The dosimeters were calibrated to 20-mrem bare ^{252}Cf. The dosimeters were then irradiated to doses of 5, 10, 15, 20, and 25 mrem and processed on each reader and reset.

The dosimeters were divided into a set of high (16−22 bubbles/mrem) and a set of low (1.2−5.3 bubbles/mrem) sensitivity. Shown in Fig. 4 are the average readings for the dosimeters normalized to their 20-mrem calibration with error bars plus and minus one sigma of the mean. It was observed that a significant over-response occurred on the order of 80 to 100% for the high-sensitivity bubble dosimeters at the 5-mrem level relative to the 20-mrem calibration. The low-sensitivity bubble dosimeters exhibited about a 40% over-response at 5-mrem relative to the 20-mrem calibration. The over-response is probably due to a more efficient counting by the bubble readers image analysis system when fewer bubbles are present. The bubble reading systems are apparently more efficient at counting nearly all bubbles present in the low-sensitivity dosimeters over the entire dose range when compared to the high sensitivity dosimeters relative to the 20-mrem calibration. The high-sensitivity dosimeters exhibit an increasing loss of counting events beyond the 5-mrem level over the entire dose range. This is presumably due to overlapping of bubbles on the two-dimensional image during automated analysis. For this reason, the low-sensitivity bubble dosimeters exhibited the least deviation from a relative sensitivity of 1.0 over the range of 5 to 25 mrem.

The mean values of the relative sensitivity were consistently within two sigma for each sensitivity class when read on different reader systems. This indicates that the reader systems produced essentially equivalent results whether the dosimeters were processed in reader No. 1 or reader No. 2.

The conclusion of this study is that the low-sensitivity bubble dosimeters offer the least deviation in relative sensitivity over the occupational dose range of concern

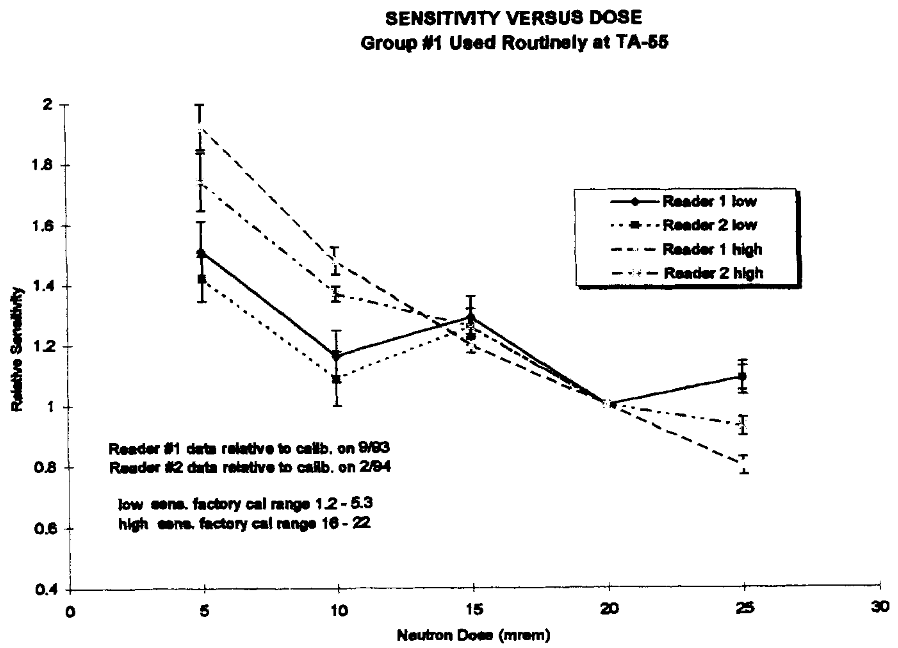

Figure 4. Results of deviation in relative sensitivity study for group No. 1, BD-100R bubble dosimeters that were used routinely at TA-55.

from 5 to 25 mrem. Bubble dosimeters are expected to over-respond at doses that are less than their calibration due to the increased counting efficiency observed when fewer counting events are present. This phenomenon is important in the analysis of the operational field data that follows.

Operational comparison of bubble dosimeters with whole-body TLDs

Bubble dosimeters were issued on a daily basis to employees of LANL's Heat Source Technology Group (NMT-9) who were producing the RTGs from 1993 to 1996 for NASA's Cassini space mission. Data on the daily bubble dosimeter readings for employees were collected and reported to ALARA personnel in NMT-9. Some employees worked for NMT-9 during this entire period of time while others came on and/or left the project during this period. These data are labeled with random employee numbers because of the sensitive nature of this personnel information. The daily bubble dosimeter readings were summed for each month and compared to the monthly whole-body TLD readings. The cumulative monthly results were tabulated and are presented in Table 1 as an overall comparison for the entire monitoring period. It was found that the average of the absolute values of the percent difference of the two measurement systems (Table 1, column 4) was 25%. As is evident from column 4 of Table 1, significant variations on the TLD and bubble dosimeter agreement occurred on an individual basis.

For cumulative doses exceeding 100 mrem, the bubble dosimetry results were within 50% of the TLD results with a couple of exceptions. Column 5 of Table 1 indicates the NCF or range of NCFs used in the whole-body TLD neutron assignments. The degree of agreement between the two measurement systems is a result of (1) a combination of technical limitations of each measurement system, (2) the diligence of the employees in donning the daily bubble dosimeters, (3) the difficulty in maintaining static NCFs during part of the monitoring period, (4) the appropriateness of the assigned NCF during the monitoring period, and (5) the accuracy of an integrated NCF.

The results of Table 1 are presented in a scatter plot format in Fig. 5. Fig. 5 shows that there is general agreement in the bubble and whole-body TLD results with the deviation of some individual results from linearity evident. As reported earlier in this paper, the method of determining the NCF changed in late 1995 from a specific assigned factor to one calculated using the integrated reading on the supplemental Model 8823 dosimeter. The implementation of the supplemental Model 8823 dosimeter had the effect of lowering the average NCF. It was observed following implementation of the Model 8823 NCF calculation method that the bubble dosimetry results tended to be significantly higher than whole-body TLD neutron results. Table 2 shows the results comparing the cumulative bubble dosimetry readings with whole-body TLD neutron results following implementation of the Model 8823 dosimeter in the fall of 1995.

The result of using the Model 8823 dosimeter had the effect of increasing to 37% the average of the absolute values of the percent difference between the two measurement systems (Table 2, column 4). The bubble dosimeters were higher 84% of the time. The resulting increased over-response of the bubble dosimetry relative to the TLD dosimetry since October 1995 is to be expected following analysis of the daily bubble dosimetry readings. Typically, daily bubble dosimeter doses for employees were less than 20 mrem. The data indicated that typical daily bubble dosimeter readings were usually in the region from 1 to 15 mrem where these dosimeters were found to over-respond relative to the 20-mrem calibration value. The degree of over-response is dependent both on the measured dose level and the sensitivity of the dosimeter used as shown in Figure 4.

CONCLUSION

This study has shown that the field use of the bubble dosimeters

Table 1. Cumulative TLD and bubble dosimetry results by employee for the entire monitoring period (1993–1996).

Individual	TLD neutron dose (mrem)	Bubble neutron dose (mrem)	Percent difference from TLD	Range of NCFs
EMP1	234	138	−41.03	0.4
EMP2	2460	2633	7.03	0.2
EMP3	804	532	−33.83	0.2, 0.4, 0.7
EMP4	691	1037	50.07	0.4, 0.5, ~0.20
EMP5	0	17		0.4
EMP6	1046	873	−16.54	0.21, 0.4
EMP7	282	188	−33.33	0.2, 0.4
EMP8	892	1047	17.38	~0.20
EMP9	489	731	49.49	0.5, ~0.20
EMP10	2155	1706	−20.84	~0.20
EMP11	20	15	−25.00	0.4
EMP12	288	254	−11.81	0.2
EMP13	2266	2202	−2.82	0.4, 0.7, ~0.20
EMP14	1235	1554	25.83	0.4, ~0.21
EMP15	41	34	−17.07	0.4
EMP16	1045	1068	2.20	0.2
EMP17	1247	1387	11.23	0.5, 0.4, ~0.25
EMP18	2370	2546	7.43	0.4, ~0.21
EMP19	461	757	64.21	0.4, ~0.24
EMP20	1789	2384	33.26	0.2, 0.5
EMP21	1790	1602	−10.50	0.2, 0.21
EMP22	22	22	0.00	0.2
EMP23	250	171	−31.60	0.4
EMP24	13	28	115.38	0.2
EMP25	21	67	219.05	0.2
EMP26	1423	1894	33.10	0.4, ~0.24
EMP27	2343	2605	11.18	0.2, 0.3
EMP28	119	125	5.04	0.4
EMP29	1286	934	−27.37	0.2, 0.5
EMP30	2376	2519	6.02	0.4, 0.20
EMP31	285	313	9.82	0.2
EMP32	1122	981	−12.57	0.2
EMP33	1319	1306	−0.99	0.2
EMP34	253	182	−28.06	0.4
EMP35	60	89	48.33	0.2
EMP36	2142	2188	2.15	~0.21
EMP37	169	180	6.51	0.2
EMP38	591	555	−6.09	0.4
EMP39	556	512	−7.91	0.4
EMP40	1337	1585	18.55	0.2
EMP41	1551	1077	−30.56	0.2, 0.4
EMP42	365	202	−44.66	0.4
EMP43	188	208	10.64	0.4
EMP44	1016	897	−11.71	0.4
EMP45	84	114	35.71	0.2, 0.5
EMP46	1597	1670	4.57	0.7, 0.4, ~0.21
EMP47	1876	1373	−26.81	0.4, ~0.21
EMP48	875	848	−3.09	0.2
EMP49	0	0.3		0.5
EMP50	974	1049	7.70	0.2
EMP51	1849	2364	27.85	~0.20
EMP52	2194	2490	13.49	0.3, 0.4, 0.2
EMP53	58	54	−6.90	0.4
EMP54	1354	1448	6.94	0.2
EMP55	1926	2308	19.83	0.2
EMP56	1262	929	−26.39	0.2, 0.4
Total	54461	55992	[a] 393	
Average	972	1000	[a] 7.3	
Variance	629363	733588	[a] 1697	
Std Deviation	793	856	[a] 41	

[a] Excludes EMP5 and EMP49.

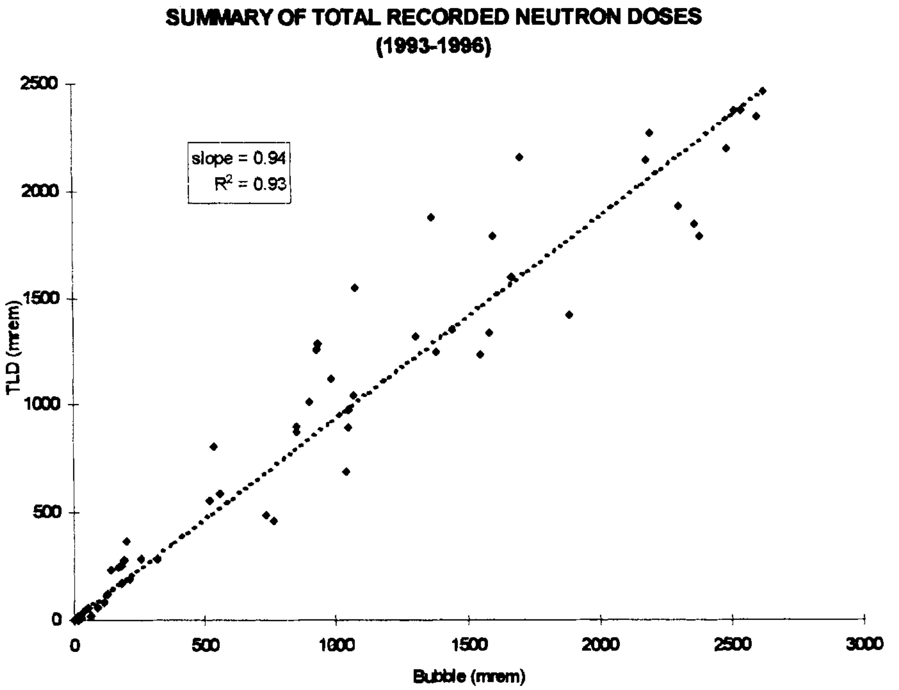

Figure 5. Cumulative TLD vs. bubble dosimetry results by employee for the entire monitoring period (1993–1996).

is an excellent ALARA tool that has been used at LANL to identify specific "high-dose" processes and make immediate improvements and reductions in dose. Bubble dosimeters offer an excellent neutron energy response requiring no correction to the readings when calibrated with bare ^{252}Cf for neutron energies from about 200 keV to several MeV. Bubble dosimeters offer real-time feedback to the employee on the magnitude of dose incurred in the workplace. However, limitations of bubble dosimeters have prevented more widespread use of these detectors for the dose-of-record in the United States. Some important limitations include relatively narrow dose range, shock sensitivity, cost, longevity, and daily reading requirements.

Cumulative daily bubble dosimetry results for monitored employees in an operational environment were found to be within 37% of whole-body TLD results on average when using the new integrated NCF calculation. Further improvement in the agreement between bubble dosimetry results and TLD can be achieved by doing two things: first, by establishing a

Table 2. Cumulative TLD and bubble dosimetry results by employee following the implementation of Model 8823 dosimeter (Oct. 1995–May 1996).

Individual	TLD neutron dose (mrem)	Bubble neutron dose (mrem)	Percent difference from TLD	NCF
EMP2	1087	1270	16.84	0.2
EMP4	542	1037	91.33	0.4, 0.5, ~0.2
EMP6	290	183	−36.90	0.4, 0.21
EMP8	892	1047	17.38	0.2
EMP9	489	731	49.49	0.19, 0.20, 0.5
EMP10	559	544	−2.68	0.19, ~0.20
EMP13	241	323	34.02	0.19, 0.20
EMP14	602	876	45.51	0.19, 0.22, 0.40
EMP16	1045	1068	2.20	0.2
EMP17	555	721	29.91	~0.25, 0.40
EMP18	452	810	79.20	0.19, ~0.21
EMP19	461	757	64.21	~0.24, 0.4
EMP20	942	1212	28.66	0.2
EMP21	303	168	−44.55	0.2
EMP26	354	635	79.38	~0.24
EMP27	867	933	7.61	0.2, 0.3
EMP30	797	967	21.33	0.19, ~0.21
EMP36	890	656	−26.29	~0.22
EMP40	231	310	34.20	0.2
EMP46	316	506	60.13	0.18, ~0.21
EMP47	435	499	14.71	0.19, ~0.21
EMP51	799	1077	34.79	0.19, ~0.20
EMP52	705	1004	42.41	0.2, 0.3
EMP54	805	952	18.26	0.2
EMP55	1040	1447	39.13	0.2
Total	15699	19733		
Average	628	789	28	
Variance	74029	114143	1160	
Std Deviation	272	338	34	

protocol to correct for the deviation in relative sensitivity at low doses for bubble dosimeters or for calibrating the dosimeters closer to expected dose levels; and, second, by ensuring that employees wear bubble dosimeters during the entire monitoring period where neutron exposure is possible and that they exchange the bubble dosimeters on a daily basis. However, the limitations and inaccuracies on both dosimetry system types will always prevent an exact one-to-one correlation between the results of each system in an operational environment.

Albedo TLD does not offer the same advantageous energy response function as bubble dosimeters neither with the use of static NCFs nor with an integrated NCF dosimeter design. However, albedo dosimeters do offer the advantage of a stable, passive integrating device that does not have the other serious limitations associated with bubble dosimeters. For this reason, albedo dosimeters continue to be used as the dose-of-record in the United States more often than bubble dosimeters.

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