ORNL--6597

DE91 004978

Health and Safety Research Division

1989 NEUTRON AND GAMMA PERSONNEL DOSIMETRY INTERCOMPARISON STUDY USING RADCAL SOURCES

C. S. Sims[1]
W. H. Casson[1]
H. Murakami[2]
J. C. Liu[3]
G. R. Patterson[4]

[1]Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6379.
[2]Dept. of Health Physics, JAERI, Tokai, Naka-Gun, Ibaraki 319-11, JAPAN.
[3]Stanford Linear Accelerator Center, Bin 48, SLAC, P.O. Box 4349, Stanford, CA 94309.
[4]Deceased.

DATE PUBLISHED - OCTOBER 1990

Prepared for the
Physical and Technological Research Division
Office of Health and Environmental Research
Budget Activity No.: KP0101000

Prepared by the
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6285
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

The authors acknowledge the detailed work of Linda R. Pyles in preparation of this manuscript which contains so many tables and so much numerical analysis. We also gratefully acknowledge Dr. R. W. Wood, Director of the Physical and Technological Research Division of the U. S. Department of Energy, for funding the ongoing series of Personnel Dosimetry Intercomparison Studies.

1989 NEUTRON AND GAMMA PERSONNEL DOSIMETRY INTERCOMPARISON STUDY USING RADCAL SOURCES

C. S. Sims[1]
W. H. Casson[1]
H. Murakami[2]
J. C. Liu[3]
G. R. Patterson[4]

HIGHLIGHTS

The fourteenth Personnel Dosimetry Intercomparison Study (i.e., PDIS 14) was conducted during May 1-5, 1989. A total of 48 organizations (33 from the U.S. and 15 from abroad) participated in PDIS 14.

Participants submitted by mail a total of 1,302 neutron and gamma dosimeters for this mixed field study. The type of neutron dosimeter and the percentage of participants submitting that type are as follows: TLD-albedo (40%), direct interaction TLD (22%), track (20%), film (7%), combination (7%), and bubble detectors (4%). The type of gamma dosimeter and the percentage of participants submitting that type are as follows: TLD (84%) and film (16%).

Radiation sources used in the six PDIS 14 exposures included ^{252}Cf moderated by 15-cm D_2O, ^{252}Cf moderated by 15-cm polyethylene (gamma-enhanced with ^{137}Cs), and $^{238}PuBe$. Neutron dose equivalents ranged from 0.44-2.63 mSv and gamma doses ranged from 0.01-1.85 mSv.

One $^{252}Cf(D_2O)$ exposure was performed at a 60° angle of incidence (most performance tests are at perpendicular incidence). The average neutron dosimeter response for this exposure was 70% of that at normal incidence. The average gamma dosimeter response was 96% of that at normal incidence.

A total of 70% of individual reported neutron dosimeter measurements were within ±50% of reference values. If the 0.01 mSv data are omitted, approximately 90% of the individual reported gamma measurements were within ±50% of reference values.

[1]Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6379.
[2]Dept. of Health Physics, JAERI, Tokai, Naka-Gun, Ibaraki 319-11, JAPAN.
[3]Stanford Linear Accelerator Center, Bin 48, SLAC, P. O. Box 4349, Stanford, CA 94309.
[4]Deceased.

INTRODUCTION

The fourteenth in a series of annual neutron and gamma Personnel Dosimetry Intercomparison Studies (i.e., PDIS 14)[1-4] was conducted at the Oak Ridge National Laboratory (ORNL) during May 1-5, 1989. The Dosimetry Applications Research (DOSAR) Group staff conducted PDIS 14 using ^{238}PuBe and ^{252}Cf (with two different moderators) neutron sources and a ^{137}Cs source available in the new Radiation Calibration Laboratory (RADCAL)[5]. The PDIS have traditionally been conducted using the Health Physics Research Reactor (HPRR)[6-7] as the radiation source. However, all research reactors at ORNL (including the HPRR) were shut down by order of the Department of Energy on March 26, 1987. Because the reactor had not been restarted at the scheduled time of PDIS 14, the study was conducted entirely at RADCAL. Depending on HPRR availability, future PDIS may involve irradiations at RADCAL as well as the HPRR.

In general, ORNL intercomparisons are designed to allow participants to test their dosimetry systems under various conditions and to compare their results with those of others making measurements under identical conditions and with reference dosimetry. The PDIS are intended to provide more comprehensive tests of the neutron-gamma abilities of dosimetrists and their dosimetry systems than are the National Voluntary Laboratory Accreditation Program (NVLAP)[8] and the Department of Energy Laboratory Accreditation Program (DOELAP)[9]. It is hoped that, because of the variety of exposure conditions, the PDIS will provide a learning experience for all participants. In particular, various PDIS 14 test conditions mocked up typical NVLAP and DOELAP exposures, repeated those exposures with different scattering conditions, caused participants to have to deal with non-perpendicular incidence of radiation, used extremes of neutron-to-gamma ratios, provided a very hard neutron energy spectrum, and provided a spectrum for which it is doubtful that any participants had previously calibrated.

In PDIS 14, personnel neutron and gamma dosimeters were mailed by participants to ORNL. The dosimeters were exposed at RADCAL to neutron dose equivalents in the 0.44-2.63 mSv (44-263 mrem) range and gamma dose equivalents in the 0.01-1.85 mSv (1-185 mrem) range. Following exposure, the dosimeters were returned to the participants for evaluation. This document is a summary and analysis of results reported to the DOSAR staff by PDIS 14 participants.

PARTICIPATION

A total of 48 organizations, 33 from the United States and 15 from abroad, participated in this PDIS. Of the 48 participating organizations, 41 reported their results to the DOSAR staff. These 41 included government laboratories (14), nuclear utilities (12), dosimeter vendors (6), universities (4), medical facilities (2), and an industrial organization (1). To ensure anonymity, they are identified by numbers in the data summary tables and discussion.

DOSIMETER TYPES

The 48 participating organizations submitted 62 sets of 21 dosimeters each (some submitted more than one badge type). A set of 21 dosimeters consisted of 3 background (or control) dosimeters and 3 dosimeters for each of the 6 exposures. A total of 1,302 dosimeters were handled by the DOSAR staff: 186 were controls and 1,116 were actually exposed to radiation. Measured neutron results were reported for 722 of the exposed dosimeters and measured gamma results were reported for 755 of the exposed dosimeters.

Figure 1 shows the collection of dosimeters submitted by PDIS 14 participants. In the figure, 59 of the 62 dosimeters shown are divided into groups by type of organization submitting that dosimeter: Department of Energy (DOE) labs, nuclear utilities, vendors and others, universities, and outside USA. Three others, identified as bubble detectors[10-11], are shown separately because this is the first PDIS in which this new type of personnel neutron dosimeter has been used.

As can be seen from Figure 1, relatively few of the badge designs are the same. However, the neutron detection mechanisms can be divided into six categories: direct interaction thermoluminescent dosimeters (TLD), TLD albedo, recoil track, film, combination, and bubble detectors (also called superheated drop). The TLD albedo and the direct interaction TLD, which have traditionally been the most popular types of neutron dosimeters used in the ORNL intercomparisons, were used by 40% and 22%, respectively, of the organizations reporting results. These TLD systems almost exclusively used the traditional Panasonic ($^6Li_2{}^{10}B_4O_7$) or Harshaw (^{6}LiF) materials as the primary neutron detection elements. Recoil track dosimeters (mainly CR-39 material) were used by 20% of the reporting organizations, film dosimeters (Kodak NTA type) were used by 7%, combination dosimeters (two TLD albedo-track dosimeters and a TLD albedo-bubble detector) were used by 7%, and bubble detectors were used by 4% of those reporting neutron results. Readily accessible literature contains excellent descriptions and discussions of the various types of neutron dosimeters.[12-14]

Concerning reported gamma results, 84% of the reporting organizations used TLD systems and 16% used film (primarily Kodak type 2, but one used Fuji type G-3). About 54% of the TLD badges used $CaSO_4$ alone or in combination with $Li_2B_4O_7$, 35% used ^{7}LiF (TLD-700) material, 8% used natural LiF (TLD-100), and about 3% (one organization) used a TLD containing BeO. Information concerning gamma dosimeter types is abundant in the literature.[15-17]

EXPERIMENT DESCRIPTION

Six different types of radiation exposures were conducted at RADCAL during PDIS 14. These six are summarized in Table 1. The so-called "9/3-inch ratio" was measured using a bare $^{10}BF_3$ tube inside a 23-cm (9 inch) diameter polyethylene sphere and inside a 7.6-cm (3 inch) diameter polyethylene sphere covered with a cadmium sheet. The average neutron energies were taken from the available literature relative to the various sources except for exposure number 2 where we determined the value using Bonner sphere measurements.[18] All the information in Table 1 was provided to the participants prior to their evaluation of the exposures.

Exposures 1, 3, 4, and 5 involved radiation from ^{252}Cf moderated by 15-cm of D_2O. Figure 2 is a photograph which clearly shows the cadmium covered D_2O sphere and the dosimeters mounted on two standard 40 x 40 x 15-cm Lucite slab phantoms in an irradiation setup typical of these exposures. Exposure 2 involved ^{252}Cf radiation moderated by a 15-cm polyethylene sphere and enhanced by gammas from a ^{137}Cs source. That neutron exposure setup was similar to that shown in Figure 2 and the gamma portion of exposure number 2 was accomplished with the irradiator as shown in Figure 3. Exposure 6 involved radiation from a $^{238}PuBe$ source. Figure 4 shows a typical irradiation setup for this portion of PDIS 14.

The reader is advised that RADCAL was in the process of becoming operational when PDIS 14 was conducted. The makeshift phantom stands, evident in Figures 2-4, have since been replaced by custom designed, track mounted stands. More professional precision aligned mounts were used during the conduct of PDIS 15 in 1990.

The six exposures were designed to provide the participating dosimetrists a challenge, as well as to allow them to collect information which should prove useful in evaluating overall dosimeter performance and in preparing for broadened performance testing should that become required by NVLAP and/or DOELAP. Exposures 1 and 5 were typical of what dosimeters traditionally see in current NVLAP and DOELAP performance tests, but with varied scattering components. Exposure 3 was designed to investigate angular response and provide participants with some minimum information about their dosimeter's capabilities at nonperpendicular angles of incidence. Exposures 2 and 6 used neutron energy spectra significantly different from what is traditionally seen in performance tests and provided dosimetrists additional information concerning response to a hard (exposure 6) spectrum with a high neutron-to-gamma ratio and a soft (exposure 2) spectum with a relatively low neutron-to-gamma ratio. Results of exposure 4 should convince many dosimetrists of the importance of properly treating their dosimeter's response to thermal neutrons.

REFERENCE DOSIMETRY

Reference neutron and gamma dose equivalents for PDIS 14 are summarized in Table 2 and details are presented in the following text.

Neutron Dose Equivalent

Neutron dose equivalents ranged from 0.44 mSv (44 mrem) in exposure 6 to 2.63 mSv (263 mrem) in exposure 4. The scatter adjusted neutron reference value for exposure 2 was determined using Bonner sphere measurements. For all other exposures, the reference value for the primary beam was determined by using the National Institute of Standards and Technology (NIST) calibration of the sources and applying fluence-to-dose equivalent conversion factors. The conversion factors used were those advocated by the International Commission on Radiological Protection in Publication Number 21 (i.e., ICRP 21)[19]. Scattered neutron components were calculated for all exposures using NIST-recommended formulas[20-21]. The remainder of this section is an amplification of the information presented above.

^{238}PuBe Irradiation (exposure 6). The ^{238}PuBe source (serial number MRC Pu8Be-496) was used in exposure 6. The Monsanto Corporation determined the neutron emission rate to be $2.4(10^7)$ s^{-1} on 3/22/82. The method of determination was by the use of long counter results compared against NIST-calibrated ^{238}PuBe standard sources. The activity at the time of PDIS 14 was determined by use of the 87.4-year half-life. Using this activity, the neutron fluence rate at 1.0-m was calculated to be 180 $cm^{-2}s^{-1}$. By use of a published ^{238}PuBe neutron energy spectrum[22] and familiar techniques described elsewhere[23], we determined that the spectrum averaged fluence-to-ICRP 21 dose equivalent conversion factor is 370 pSv-cm^2 ($3.7(10^{-5})$ mrem-cm^2). Combined with the fluence rate, this yields a dose rate of 0.24 mSv/h (i.e., 24 mrem/h) at 1.0-m. The duration of the PDIS exposure was 1.75-h and resulted in a dose equivalent of 0.42 mSv (42 mrem) from the primary beam. The 5% scattering contribution

to the total dose equivalent was calculated following Eisenhauer's documented techniques[21]. The ^{238}PuBe irradiation was done 1.38-m above the concrete floor in the low scatter aluminum room of building 7712 adjacent to RADCAL. Consequently, only single surface scatter from the concrete floor was considered in the calculation (walls and ceiling were not included). The appropriate room scatter equation is

$$R = 2ab(\cos y)(r/h)^2 = 0.04 \qquad (1)$$

where R = relative dose equivalent response for scattered and primary beam neutrons

a = albedo of reflecting surface (taken to be 0.54)[20-21]

b = combined anisotropy and spectral response factor (taken to be 0.37)[20-21]

cos y = cosine of the specular angle y (0.94 in this case)

r = source-to-dosimeter distance (1-m)

h = source-to-image source distance (2.936-m)

The air scatter for this hard source[21] is approximately 1%/m. At 1m, this 1% is added to the 4% room scatter for the total of 5% mentioned above and shown in Table 2.

<u>D_2O Moderated ^{252}Cf Irradiations (exposures 1, 3, 4 and 5)</u>. The ^{252}Cf source designated NSD-107 was used in exposures 1, 3, 4 and 5. The source emission rate was determined by NIST to be $7.63(10^9)$ s^{-1} on 4/30/87. Activity at the time of PDIS 14 was determined by use of the 2.64-y half-life to be $4.51(10^9)$ s^{-1}. The spectrum averaged fluence-to-dose equivalent conversion factor was taken to be 90.8 pSv-cm^2 ($9.08(10^{-6})$ mrem-cm^2).[23-24] In general, the neutron dose equivalent due to the primary beam from the D_2O-moderated, cadmium-covered, ^{252}Cf source is given by the expression[25]

$$H_{npo} = NCt(3600)(0.885)/4\pi r^2 \qquad (2)$$

where N = neutron emission rate, s^{-1}

C = conversion factor, mrem-cm^2

t = exposure time, h

r = source-to-phantom distance, cm

0.885 = factor to allow for loss of neutrons below cadmium cutoff.

Exposure 1 was performed with the phantoms at 1.5 m from the source. Using Eqn. (2), the exposure time of 9 minutes resulted in $H_{npo} = 69(10^{-5})$ Sv (i.e., 69 mrem) as recorded in Table 2. The RADCAL neutron room is essentially a rectangular, concrete-enclosed room. Following Eisenhauer[21], the appropriate room scattering equation is

$$R = 4.5b(r/r_c)^2 \qquad (3)$$

where r_c is defined by the equation

$$4\pi r_c^2 = \sum A_i \qquad (4)$$

and R = relative dose equivalent response to scattered and primary beam neutrons

b = combined anisotropy and spectral response factor (taken to be 0.49)[20-21]

r_c = radius of spherical cavity which has the same surface area as the actual calibration room (calculated to be 5.5 m)

A_i = area of the ith surface of the calibration room, m^2

r = source-to-detector distance, m

For r = 1.5m, R = 0.164. Air scatter for this moderated source[21] is taken to be 1.5%/m. At 1.5m, this 2.25% added to the 16.4% room scatter results in the 19% total scatter component for exposure 1 recorded in Table 2. If future attempts are made to refine the calculation of R, it should be recognized that the shielding in the RADCAL neutron room ceiling is significantly less than that in the walls and floor. Detailed analysis of that could lead to a slight modification of the r_c value used above.

Exposure 5 was performed with the phantoms at 0.75 m from the source. Using this information in Eqn. (2), the exposure time of 8 minutes resulted in $H_{npo} = 246(10^{-5})$ Sv (i.e., 246 mrem) as recorded in Table 2. Using r = 0.75m, the room scatter was calculated via Eqn. (3) to be about 4.1%. At 1.5%/m, the air scatter at 0.75m was determined to be 1.1%. Consequently, the total scatter component reported in Table 2 is 5%.

Exposure 3 was identical to exposure 5 except the phantom was rotated 60° clockwise about the vertical centerline of the surface of the phantom which was kept at 0.75m from the source. The dosimeters were mounted along the vertical centerline to assure that they would all be exposed equidistant from the source. The dose equivalent reported in Table 2 at this 60° angle is that at perpendicular incidence. The effective dose equivalent (which is legally used in limiting personnel exposure) actually decreases as a function of angle away from perpendicular, but the appropriate dosimetric behavior has not yet been approved by authoritative bodies. The results of this study will, however, allow participants to determine their dosimeter's relative response at 60°.

Exposure 4 was identical to exposure 5 except the thin cadmium shell was removed from the D_2O-filled steel sphere. As previously stated, 88.5% of the D_2O-moderated ^{252}Cf neutrons are above the cadmium cutoff energy. Therefore, removing the cadmium shell increases the fluence by 11.5%. To determine the associated increase in dose equivalent, equation 2 may be used with the ICRP 21 fluence-to-dose equivalent conversion factor appropriate for thermal neutrons: 10.7 pSv-cm^2 (i.e., 1.07 x 10^{-6} mrem-cm^2). Using values already presented, the ratio of the dose equivalent from the primary beam for the "without cadmium" exposure to that with cadmium is:

$$\frac{H(wo)}{H(w)} = \frac{0.885(9.08) + 0.115(1.07)}{0.885(9.08)} = 1.015 \qquad (5)$$

This means that removing the cadmium cover increases the neutron fluence by 11.5%, but only increases the dose equivalent by 1.5%. The scattered component is assumed to be the same as that reported for exposure 5 and the results are tabulated in Table 2.

Polyethylene Moderated ^{252}Cf Irradiation (exposure 2). The ^{252}Cf source designated NSD-87 was used in exposure 2. The source emission rate was determined by NIST to be 2.51(10^9) s^{-1} on 5/6/87. Activity at the time of PDIS 14 was determined by use of the 2.64-y half-life. The NSD-87 source was inserted in a 15-cm diameter polyethylene sphere and positioned such that the source centerline was

1.83-m above the floor. Reference dosimetry for this irradiation was determined by measurements made with a Bonner multisphere spectrometer[26]. The measurements were a joint effort between Dr. Ferenc Hajnal of the Environmental Measurements Laboratory and the DOSAR staff. The dose equivalent rate at 1-m from the source was determined to be 1.8 mSv/h (180 mrem/h) at the time of PDIS 14[27]. The 20 minute irradiation resulted in a total dose equivalent of 0.60 mSv (60 mrem). Details associated with the measurement and analysis are being published elsewhere[28].

The measured results considered above included room and air scatter. To calculate the scatter contribution to the total, a simplifying assumption was made since values for needed parameters in the scattering equations were not available for this unusual polyethylene moderated source. Since the average energy for this source-moderator combination was found by the multisphere measurements to be intermediate between bare and D_2O-moderated ^{252}Cf, it was assumed that the scattering contribution would also be intermediate between them. At 1-m, the total scattering from the D_2O-moderated ^{252}Cf source in RADCAL was calculated by techniques used above to be 9%. For bare ^{252}Cf, it was calculated to be 7%. It was, therefore, assumed that the scattering for this source at 1-m is 8% as indicated in Table 2.

Gamma Dose Equivalent

As seen in Table 2, gamma dose equivalents in PDIS 14 ranged from 0.01-1.85 mSv (1-185 mrem). Neutron-to-gamma dose equivalent ratios varied from 0.32 in exposure 2 to 44.0 in exposure 6.

Reference gamma dose equivalents for all six mixed-field exposures were measured with a Phillips No. 18509 Geiger-Mueller (GM) counter[29] mounted directly on a Lucite slab phantom. The GM counter is 1.6 cm long and 0.48 cm in diameter. It has been shown that the neutron dose response

of this counter is <0.5% of the gamma dose response. The GM counter was calibrated with the ^{137}Cs irradiator shown in Figure 3.

The gamma dose equivalent rate associated with the ^{137}Cs irradiator is traceable to NIST. The reference gamma dose equivalent for the ^{137}Cs-enhanced portion of exposure 2 was determined from the exposure time and the NIST-related dose equivalent rate.

RESULTS AND ANALYSIS OF NEUTRON MEASUREMENTS

Tables 3-8 summarize reported neutron results for each exposure. Irradiation data given in these tables include exposure number, source, and reference neutron dose equivalent in the ICRP 21 convention. Results shown for each participant consist of numbered organization identification, neutron dosimeter type, reported dose equivalents for each mounted badge, and the average of all reported results. Neutron dosimeter performance characteristics described below were derived from the basic data presented in these tables.

Analyses of reported neutron measurements are presented in Tables 9-14 for the composite of all results, for the subset of results which were less than three times the reference value, and for each of the six neutron dosimeter types used in this study. In these tables, data given for each exposure include the reference neutron dose equivalent, the number of participants reporting results, the range of normalized (measured divided by reference) results, and the mean and one standard deviation about the mean of the normalized measurements. Figures 5 and 6 graphically present some of the data contained in Tables 9-14. The data are discussed below under headings associated with each neutron dosimeter type used in the study as well as the composite of all neutron results.

TLD

About 22% of the participants in PDIS 14 measured neutrons using direct interaction TLD's. The majority of these were Panasonic type UD-802. Notice that these are not TLD albedo dosimeters which are considered below. The average results plotted in Figure 5 show that TLD's overresponded by about 30-50% for the $^{252}Cf(D_2O)$ exposures (i.e., 1, 4, and 5) and that the presence or absence of the cadmium shell made surprisingly little difference (it caused an increase of about 10% on the average). The best TLD results were for the PuBe exposure where the average overresponse was only 11%. The poorest accuracy was for the polyethylene moderated ^{252}Cf exposure (i.e., number 2) where the average overresponse was more than a factor of 2. In general, these types of dosimeters do a good job when the calibration field is the same as the measured field, but many in current use have limited capability to distinguish a variety of experimental conditions. These TLD's exhibited a relatively moderate angular dependence in that the dose equivalent at 60° incidence was about 66% of that at perpendicular incidence (compare exposures 3 and 5).

TLD-albedo

About 40% of PDIS 14 participants used TLD albedo dosimeters to determine the neutron dose equivalent. From Figure 5, it is seen that the average results overestimate the actual dose equivalent from 15-57% for the 5 exposures made at perpendicular incidence. The average TLD albedo dosimeter, like the direct interaction TLD's, exhibited a moderate angular dependence. The dose equivalent at 60° incidence was, on the average, 62% of that at perpendicular incidence. The overall response of the TLD albedo dosimeters was remarkably close to, but perhaps slightly better than, that of direct interaction TLD's for all exposures except number 2, the polyethylene moderated irradiation. The albedo results were significantly better (overresponse by a factor of 1.57 as opposed to a factor of 2.16) than those for direct interaction TLD's for that exposure. Like direct interaction TLD's, the TLD albedo dosimeters' response to exposure 4 (the no-cadmium exposure) was only about 10% larger than the response to exposure 5. We at DOSAR were concerned that the 11% increase in

thermal neutron fluence in exposure 4 over that in exposure 5 would lead participants using TLD and TLD albedo systems to significantly overrespond due to their high sensitivity to low energy neutrons. On the average, PDIS 14 results show that situation did not occur.

Track

Examination of Figure 5 indicates track dosimeter results were generally the least accurate of any of the neutron dosimeter types used in PDIS 14. They overresponded in every case and the overresponse increased monotonically with increasing spectrum hardness. The results (Tables 9-14) also show that the track measurements have the largest standard deviations of any of the neutron dosimeter types. The reader is reminded that these results are composite ones for all the track dosimeters used in PDIS 14 and that, as for other dosimeter types, some individual participants reported very good results using track dosimeters. Exposures 3 and 5 were identical $^{252}Cf(D_2O)$ exposures except 3 was done at a 60° angle of incidence. The track dosimeters exhibited a strong angular dependence. The average 60° incidence response was 54% (1.06/1.95) of that at perpendicular. The effect of the removal of the cadmium shell can be determined by comparing results of exposure 4 (without cadmium) to those of exposure 5. Average track results were generally about 10% higher for exposure 5 than for 4, but the numbers are well within one standard deviation of each other. Since track dosimeters don't measure thermal neutrons, the numbers were expected to essentially be the same.

Film

About 7% of PDIS 14 participants used film (all Kodak NTA) to measure neutron dose equivalents. Examination of the results plotted in Figure 5 reveals that the overall film results were the most accurate of all dosimeter types for the two hardest spectra in the study (i.e., exposures 2 and 6). The mean measured results normalized to reference values were 0.96 ± 0.48 and 1.08 ± 0.20, respectively, for these exposures. Film, being a threshold-type dosimeter, is much better suited for the measurement of hard spectra than for soft. In addition, those participants who used film calibrated

their dosimeters with either PuBe or AmBe. Had they calibrated with $^{252}Cf(D_2O)$, they probably would not have overresponded by a factor of 1.6-2.2 like they did for exposures 1, 4, and 5. Like track dosimeters, film exhibited a strong angular dependence: the average response at 60° (exposure 3) was only 43% of that at perpendicular incidence (exposure 5). Again like track dosimeters, the presence or absence of the cadmium shell (exposures 5 and 4) made little difference (results were 12% higher with the shell in place, but they were well within one standard deviation).

Bubble

Two participant groups (numbers 2 and 21) used bubble detectors to measure neutron dose equivalent. A third group (number 26) used a bubble detector-TLD albedo combination, but their results are included in the combination dosimeter category. The bubble detectors tested were of different types: the one used by group number 2 was a direct reading type (moveable plunger pointed to dose equivalent value) and the other was a "count the bubbles" type. The measured results displayed very low standard deviations for all six exposures. As seen in Figure 5, the mean measured results were generally low by about 30%. A calibration factor change could easily correct this since the results were relatively consistent across the range of spectra used in PDIS 14. The results were, however, somewhat more accurate for harder spectra than for soft.

Combination

Three participant groups (17, 26, and 41B) used combination dosimeters in this study. Combination units are designed to use the best capabilities of two types of dosimeters in covering a wide range of neutron energy spectra. It is, therefore, not surprising that, on average, the combination dosimeters were the most accurate neutron dosimeters for PDIS 14 exposures 1-5 (see Figure 5). The mean measured dose equivalents were within 20% of reference values and the standard deviations were low. The poor results (average overresponse by a factor of 2.5) for exposure 6 are attributed to one TLD albedo-track reading which was high by a factor of 5.23. At PuBe energies, such combination units

typically rely on the track portion of the dosimeter. At low doses like that in exposure 6 (i.e., 44(10^{-5}) Sv), generally available track dosimeters have not performed well in hard spectra[30].

Composite of Neutron Results

A subset of all neutron reported results is presented in Figure 6 for each of the PDIS 14 exposures. The subset eliminates all results (about 7% of those reported) which were greater than three times the reference values. Overall, the most accurate measurements were made for exposure 6 (PuBe). This exposure had the hardest neutron energy spectrum and, interestingly enough, the lowest dose equivalent (44 x 10^{-5}Sv). Exposure 4, with 263(10^{-5})Sv, had the largest dose equivalent, but the measurements were the least accurate overall. This exposure had the softest spectrum. Harder spectra led to more accurate measurements. The average response to $^{252}Cf(D_2O)$ neutrons at 60° incidence was 70% of that at perpendicular incidence (the reader is reminded that this is a subset of all results). The average response to $^{252}Cf(D_2O)$ without the cadmium sheet was greater than that for the "with cadmium" exposure by 15%.

RESULTS AND ANALYSIS OF GAMMA MEASUREMENTS

Gamma results reported for the six mixed radiation fields encountered in PDIS 14 are summarized in Tables 15-20. Data presented in these tables include exposure number and reference gamma dose equivalent. Results shown for each participant include the organization identification number, gamma dosimeter type, gamma dose equivalent for each mounted badge, and the average of all reported results. Gamma dosimeter performance characteristics described below are based on the data presented in these tables. Figures 7 and 8 graphically present some of the data contained in Tables 21-26.

Analyses of reported gamma measurements are presented in Tables 21-26 for the composite of all results and for the basic dosimeter types used in PDIS 14. Data shown in each table include the reference gamma dose equivalent, the number of participants reporting results, the range of normalized results, and the mean and one standard deviation about the mean of the normalized measurements. The data are discussed below under headings associated with each of the gamma dosimeter types used in PDIS 14 as well as the composite of all gamma results. It should be pointed out that not too much should be inferred from exposure 6 since the reference gamma component was only 10^{-5}Sv (1 mrem).

TLD-100

Three participants (numbers 11, 42A, and 42B) used TLD-100 to measure the gamma component in these mixed field neutron-gamma exposures. Being natural LiF, these dosimeters are expected to be relatively sensitive to neutrons. That explains the severe overestimation of the gamma dose equivalent as seen in Figure 7. The overresponse increases with increasing neutron-to-gamma dose equivalent ratio (N/G). The average overresponse was only about 50% for exposure 2 which was the ^{137}Cs enhanced ^{252}Cf(poly) exposure with N/G = 0.32. In the other exposures where N/G > 4, the average overresponse varied from a factor of 4.5 - 9. An examination of Tables 21-26 shows that, in some cases, individual participants reported results which were high by a factor of 22.

TLD-700

About 35% of PDIS 14 gamma measurements made with TLD's were made with TLD-700 dosimeters. The average performance is shown graphically in Figure 7. The general trend is toward increasing overresponse with increasing N/G; however, more explanation is needed. The most accurate measurements were made for the high dose equivalent (i.e., 185 x 10^{-5}Sv), low N/G (i.e., 0.32) exposure (number 2). The least accurate overall results were associated with exposure 4 (no cadmium). The average TLD-700 results for this 42(10^{-5})Sv exposure were high by a factor of 2.41. Examination of

Table 18 shows that this unexpectedly poor accuracy was due to the results of two participants, numbers 1 and 41C, being high by factors of 6.17 and 15.5, respectively. If those two results were omitted, the normalized average would be 1.02 ± 0.32. A comparison of exposures 3 and 5 shows that the dose equivalent at 60° incidence is 75% of that at perpendicular incidence (it was 76% for TLD-100).

TLD-BeO

One participant (number 8) used TLD-BeO dosimeters. Their results, except for exposures 1 and 6 where they reported ≤ $20(10^{-5})$Sv, are plotted in Figure 7. They generally underestimated the dose equivalent in exposures 2-5 by 8-29%. Their results at 60° incidence were 90% of those at perpendicular incidence.

TLD-$CaSO_4$

Near the front of this report, it was stated that 54% of PDIS 14 TLD-using participants used $CaSO_4$ either alone or in combination with $Li_2B_4O_7$. For this gamma analysis, the term "TLD-$CaSO_4$" is used to identify Teledyne-type dosimeters. The term "TLD-$Li_2B_4O_7$" is used (see the next section) to identify Panasonic-type dosimeters even though some of them use the $CaSO_4$ portion to obtain the gamma results.

According to the definition of terms we have adopted, three participants used TLD-$CaSO_4$. As seen in Figure 7, they obtained excellent results for exposures 1-3. Their average results were within 4% of reference values for these exposures and the standard deviations were small. Such values (when exposure 3 is considered) indicate a very weak angular dependence for these dosimeters in the gamma fields in which they were tested. They measured "zero" dose equivalent for exposure 6, but the reference value was only 10^{-5}Sv. Exposure 5 results indicate a dramatic overresponse. This was due to the fact that one participant (number 34) reported a value which was high by a factor of 15.8. If

that result is omitted, the average of the remaining two participants is high by only 9%. The results for the "no-cadmium" exposure (i.e., number 4) were high by <30%. Considering everything, these dosimeters performed quite well.

TLD-$Li_2B_4O_7$

As explained in the previous section, "TLD-$Li_2B_4O_7$" refers to Panasonic-type dosimeters in this analysis. In PDIS 14, 46% of TLD-using participants used this type TLD gamma dosimeter. The results, as seen in Figure 7, are lower than the reference values for exposures 1-3, and 5. They are, however, within 28% of reference values for all exposures except the 10^{-5}Sv one (number 6) where they overestimate by a factor of 3. A comparison of exposures 3 and 5 shows that the average response at 60° is 90% of that at perpendicular incidence. The average gamma response for the "no cadmium" case (exposure 4) was 11% greater than for the standard $^{252}Cf(D_2O)$ exposure (number 5). These dosimeters exhibited the best overall performance of any gamma dosimeter type for exposures 4 and 5.

Film

About 16% of PDIS 14 participants used film gamma dosimeters. As seen in Figure 7, the film response relative to reference values increases monotonically with N/G. Film results are excellent (within 8% of reference) for exposures 1-3. The overresponse increases to 27% and 47% for exposures 5 and 4, respectively. Again, exposure 6 was only 10^{-5}Sv and not much can be gained from its analysis. The response at 60° incidence was 85% of that at perpendicular incidence. It is noteworthy that the standard deviations for the film results were among the lowest of all gamma dosimeter types for all exposures.

Composite of gamma results

A subset of all gamma reported results is presented in Figure 8 for each of the six exposures. Results greater than three times the reference values (about 8% of those reported) are excluded from the analysis. Half of those excluded were from exposure 6. The composite results were very good: they ranged from 17% underresponse to 14% overresponse and generally had higher results as N/G increased. The standard deviations were reasonable and averaged about 30% of the mean for all but exposure 6. The average response at 60° incidence was 96% of that at perpendicular incidence. That indicates almost no angular dependence for the relatively hard gammas associated with these exposures. Like the composite results for neutrons, the average response to $^{252}Cf(D_2O)$ without the cadmium sheet was greater than that for the "with cadmium" exposure by about 15%.

RESULTS AND ANALYSIS OF THE TOTAL DOSE EQUIVALENT

Table 27 summarizes data from a subset of the composite total (i.e., neutron plus gamma) dose equivalents reported by participants. As before, the subset omits results which were greater than three times the reference values (about 6% of reported results were omitted). Relevant data are plotted in Figure 9. These results show that the mean total dose equivalents vary from 97-139% of reference values for the six PDIS 14 exposures. The mean results were most accurate for the $45(10^{-5})$Sv PuBe exposure (number 6), but the standard deviation was the largest. The least accurate results were obtained for the exposure to $^{252}Cf(D_2O)$ without the cadmium shell around the sphere. The average total dose equivalent was 17% higher for the exposure "without cadmium" than for the identical exposure with cadmium. Overall, the total dose equivalent for $^{252}Cf(D_2O)$ at 60° incidence was 82% of that at perpendicular incidence.

RESULTS RELATIVE TO REGULATORY CRITERIA

Results relative to two different types of regulatory criteria (one traditional, one current) are presented in this section.

Nuclear Regulatory Commission

Traditional guidance in the United States from the Nuclear Regulatory Commission[31] (NRC) suggests that personnel neutron and gamma ray dosimeters used in the dose equivalent range covered by this study should be accurate to within ±50% of reference values. A detailed examination of Tables 3-8 shows that 70% of the individual reported neutron dose equivalent measurements meet the ±50% accuracy criterion. For the traditional $^{252}Cf(D_2O)$ irradiations of exposures 1, 3, and 5, about 76% of the neutron measurements meet the criterion. For exposures 2, 4, and 6, about 64% of the measurements are within ±50% of reference values.

A similar examination of Tables 15-20 shows that 90% of the individual reported gamma dose equivalent measurements meet the ±50% accuracy guidance. This doesn't include the data for exposure 6 where only 25% of the measurements are within ±50% of the 10^{-5}Sv(1 mrem) dose equivalent value. As expected, 98% of the gamma measurements for the ^{137}Cs-enhanced exposure of 185(10^{-5})Sv (i.e., number 2) are within the accuracy guidelines.

A study of Figure 5 reveals that the mean measured neutron dose equivalents for TLD albedo neutron dosimeters meet the ±50% criterion for all six exposures. Bubble and combination dosimeter results meet the criterion for five exposures, TLD's meet it for four, film for three, and track for only one of the six exposures.

A similar study of Figure 7 shows that the mean measured gamma dose equivalents for film and TLD-$Li_2B_4O_7$ meet the ±50% guidance for five of the six exposures. TLD-BeO, $CaSO_4$, and TLD-700 meet it for four, and TLD-100 for only one of the six exposures.

National Voluntary Laboratory Accreditation Program

The National Voluntary Laboratory Accreditation Program (NVLAP)[8] requires testing of personnel dosimeters based on American National Standards Institute criteria[32]. For such testing, NVLAP requirements are that the absolute value of the normalized sum, T, of the accuracy (i.e., mean result minus reference) and the precision (one standard deviation about the mean) must be ≤0.50. PDIS 14 exposures were generally more difficult to measure than those currently required by NVLAP, but it is of interest to evaluate the results according to the NVLAP criteria.

Careful study of Tables 9-14 allows the calculation of T for the various exposures and neutron dosimeter types. When all neutron dosimeters are considered as a group, they don't meet the T≤0.50 requirement for any PDIS 14 exposure (T varied from 0.66-2.40). The same is true for the subset (T varied from 0.64-0.91). As a group, TLD albedo (T of 0.53-2.06) and track (T of 1.08-4.97) dosimeters do not meet the requirement for any exposure. TLD (exposure 3) and film (exposure 6) meet it for one exposure. Bubble dosimeters (T of 0.15-0.65) meet the requirement for three of the six exposures and combination dosimeters meet the NVLAP requirement for five exposures (only missed number 6).

A similar study of Tables 21-26 allowed the calculation of T for the various exposures and gamma dosimeter types. When all gamma dosimeters are considered as a group, they only meet the T≤0.50 requirement for PDIS 12 exposure 2 (T=0.26). The subset, however, meets the requirement for five exposures; only exposure 6 (T=0.98) failed. As a group, TLD-100 dosimeters do not meet the requirement for any exposure (T of 0.99-17.26). TLD-BeO was not considered since only one participant used that type of dosimeter. TLD-700 dosimeters meet the requirement for one exposure (number 2). Film, $CaSO_4$, and $Li_2B_4O_7$ meet the NVLAP T≤0.50 requirement for four of the six PDIS 14 exposures.

ADDITIONAL PARTICIPANT-FURNISHED INFORMATION

Most participants completed a questionnaire designed to collect additional dose equivalent determination methodology and returned it with their measured results. It was learned that all participant organizations, except two who purchase vendor services, evaluated the dosimeters in-house. Additional results of the questionnaire are summarized in the following text.

When the neutron dose equivalent is reported, it has to be reported using some particular reporting convention[23]. Seventeen participants (44% of those responding to the question) used the ICRP 21[19] reporting convention. This is the one which we primarily use at DOSAR. The convention described by the National Council on Radiation Protection and Measurements in Report No. 38[33] (i.e., NCRP 38) was used by 31% of those reporting. Four other conventions were used by 18% of those responding to the questionnaire and 7% did not know which convention was in use by their organization.

Calibration is an important part of neutron dosimetry. Twelve participants (33% of those responding) used D_2O-moderated ^{252}Cf either alone or in combination with another source to calibrate their dosimeters. Nine participants (25%) said they used ^{252}Cf (alone or in combination with others). We suspect that some of these may have actually been moderated and not just bare ^{252}Cf. AmBe sources (alone or in combination) were used by 19% of the respondents while PuBe was used by 17%. One participant (3%) used ^{137}Cs and another (3%) said they didn't use anything.

Corrections to raw readings of the neutron dose equivalent can be made in a variety of ways. We assume that all participants corrected for background and asked what other corrections were made. Eleven respondents (30%) didn't make further corrections. Six (16%) made "energy corrections." The other 20 respondents listed 9 different types of corrections they made. Among those types were fading (film users), temperature (bubble user), 9/3-inch ratio (could be an seen as an energy correction), and track size analysis.

SUMMARY AND CONCLUSIONS

The following summary and conclusions are based on PDIS 14 information presented in the text, tables, and figures.

1. More participants (40%) measured the neutron dose equivalent with TLD albedo dosimeters than with any other type. The second most used neutron dosimeter type was the direct interaction TLD (22%).

2. TLD systems of various types were used by 84% of PDIS 14 participants to measure the gamma dose equivalent. Of these, 54% were $CaSO_4$ (alone or in combination with $Li_2B_4O_7$) and 35% were ^7LiF (TLD-700).

3. More participants (44%) reported their neutron dose equivalents in the convention advocated in ICRP 21 than in any other. About 31% used the NCRP 38 dose equivalent reporting convention.

4. About 58% of participants measuring neutrons calibrated their systems with ^{252}Cf (either bare or D_2O-moderated). AmBe (19%) and PuBe (17%) were other major sources used by PDIS 14 participants.

5. PDIS 14 was the first ORNL intercomparison in which bubble detectors were used to measure the neutron dose equivalent.

6. Neutron dose equivalents were more accurately measured for hard spectra than for soft spectra.

7. Overall, measured gamma dose equivalents increased monotonically with increasing neutron-to-gamma dose equivalent ratio relative to reference values.

8. The average neutron dosimeter response to $^{252}Cf(D_2O)$ at 60° incidence was 70% of that at perpendicular incidence. As expected, track (54%) and film (60%) exhibited the strongest angular dependence.

9. The average gamma dosimeter response to $^{252}Cf(D_2O)$ at 60° incidence was 96% of that at perpendicular incidence. The value for film was 85%.

10. The average neutron dosimeter response as well as the average gamma dosimeter response to $^{252}Cf(D_2O)$ without the cadmium shell around the steel sphere was 15% greater than that with the cadmium shell.

11. A total of 70% of individual reported neutron dosimeter measurements were within ±50% of reference values. (76% of measurements were within guidelines for $^{252}Cf(D_2O)$-type exposures).

12. A total of 90% of individual reported gamma dosimeter measurements were within ±50% of reference values. (This does not consider the 10^{-5}Sv exposure number 6).

13. Based on a combination of accuracy and precision in the measurement of all PDIS 14 exposures, the neutron dosimeter types judged to have exhibited the best performance were combination, TLD-albedo, and bubble.

14. Based on a combination of accuracy and precision in the measurement of five PDIS 14 exposures (number 6 is omitted), the gamma dosimeter types judged to have exhibited the best performance were TLD-$Li_2B_4O_7$, film, and $CaSO_4$.

15. The use of TLD-100 dosimeters to measure the gamma component of mixed neutron-gamma radiation fields can lead to severe overresponse. For the six PDIS 14 exposures, the average overresponse of such dosimeters was more than a factor of 5.

REFERENCES

1. R. E. Swaja and C. S. Sims, "Neutron Personnel Dosimetry Intercomparison Studies at the Oak Ridge National Laboratory: A Summary (1981-1986)," Health Phys., 55, 549-564 (1988).

2. C. S. Sims and R. E. Swaja, "Personnel Neutron Dosimetry Intercomparison Studies at the Health Physics Research Reactor: A Summary (1974-1980)," Health Phys., 42, 3-18 (1982).

3. R. E. Swaja, L. E. West, C. S. Sims and T. J. Welty, 1987 Neutron and Gamma Personnel Dosimeter Intercomparison Study Using a D_2O-Moderated ^{252}Cf Source, ORNL-6544 (May 1989).

4. R. E. Swaja, P. S. Weng, C. S. Sims and S. H. Yeh, Summary and Analysis of the 1986 ORNL Personnel Dosimetry Intercomparison Study, ORNL-6378 (April 1987).

5. William H. Casson and C. S. Sims, "A New Dosimeter Calibration Laboratory at ORNL," in Proceedings of the Second Conference on Radiation Protection and Dosimetry, p. 206-210, ORNL/TM-10971 (October 1988).

6. C. S. Sims and H. W. Dickson, "Neutron Dosimetry Intercomparison Studies," Radiat. Prot. Dosim., 10, 331-340 (1985).

7. C. S. Sims and L. W. Gilley, "Twenty Years of Health Physics Research Reactor Operation," Nuclear Safety, 24, 678-688 (1983).

8. Robert L. Gladhill, Jeffrey Horlick and Elmer Eisenhower, The National Personnel Radiation Dosimetry Accreditation Program, U. S. Department of Commerce, National Bureau of Standards, NBSIR 86-3350 (January 1986).

9. U. S. Department of Energy, Handbook for the Department of Energy Laboratory Accreditation Program for Personnel Dosimetry Systems, DOE/EH-0026 (December 1986).

10. R. E. Apfel and Y. C. Lo, "Practical Neutron Dosimetry with Superheated Drops," Health Phys., 56, 79-83 (1989).

11. H. Ing, "The Status of the Bubble-Damage Polymer Detector," Nucl. Tracks and Radiat. Meas., 12, 49-54 (1986).

12. R. V. Griffith, D. E. Hankins, R. B. Gammage, L. Tommasino and R. V. Wheeler, "Recent Developments in Personnel Neutron Dosimeters: a Review," Health Phys., 36, 235-260 (1979).

13. H. Ing and E. Piesch, eds., "Neutron Dosimetry in Radiation Protection," Radiat. Prot. Dosim., 10, 1-345 (1985).

14. M. Sohrabi, "Review of Recent Developments in Personnel Neutron Dosimeters," Health Phys., 41, 686-689 (1981).

15. K. E. Duftschmid, "TLD Personnel Monitoring Systems-The Present Situation," Radiat. Prot. Dosim., 2, 3-12 (1982).

16. C. S. Sims and R. E. Swaja, "TLD-700 Gamma Measurements in Mixed Neutron-Gamma Radiation Fields," Radiat. Prot. Dosim., 12, 325-331 (1986).

17. Yigal S. Horowitz, Thermoluminescence and Thermoluminescent Dosimetry, Volumes I-III, CRC Press, Boca Ratan, Florida (1984).

18. H. Awschalom and R. S. Sanna, "Application of Bonner Sphere Detectors in Neutron Field Dosimetry," Radiat. Prot. Dosim., 10, 89-101 (1985).

19. International Commission on Radiological Protection, "Data for Protection Against Ionizing Radiation from External Sources: Supplement to ICRP Publication 15," ICRP Publication 21 (1973).

20. R. B. Schwartz and C. M. Eisenhauer, Procedures for Calibrating Neutron Personnel Dosimeters, U. S. Department of Commerce, National Bureau of Standards, Washington, D. C., NBS Special Publication 633 (1982).

21. C. M. Eisenhauer, J. B. Hunt and R. B. Schwartz, "Calibration Techniques for Neutron Personnel Dosimetry," Radiat. Prot. Dosim., 10, 43-57 (1985).

22. S. Block, J. Bryan, C. Prevo and D. Montan, "Laboratory Sources Enhanced in 0.5 eV to 200 keV Neutrons for Instrument Evaluation," Health Phys., 13, 1025-1031 (1967).

23. C. S. Sims, "Comparison of Neutron Dosimetric Quantities," Health Phys., 54, 551-555 (1988).

24. C. M. Eisenhauer, "Evaluation of Dose Equivalent per Unit Fluence for a D_2O-Moderated ^{252}Cf Neutron Source," Radiat. Prot. Dosim., 9, 63-64 (1984).

25. U. S. Department of Energy, Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems, DOE/EH-0027 (December 1986).

26. M. Awschalom and R. S. Sanna, "Applications of Bonner Sphere Detectors in Neutron Field Dosimetry," Radiat. Prot. Dosim., 10, 89-101 (1985).

27. James C. Liu, "^{252}Cf (Polyethylene Moderated) Dosimetry Information," internal ORNL letterot C. S. Sims (April 25, 1989).

28. James C. Liu, Ferenc Hajnal, C. S. Sims and John Kuiper, "Neutron Spectra Measurements at ORNL," submitted to Radiat. Prot. Dosim. on October 19, 1989.

29. R. Oyan and C. S. Sims, "Radiation Dose from HPRR Gamma Rays," Radiat. Prot. Dosim., 16, 213-217 (1986).

30. C. S. Sims and R. E. Swaja, "Performance Comparison of Thorium Track, Polycarbonate, and CR-39 Neutron Dosimeters," Nucl. Tracks, 10, 461-465 (1985).

31. U. S. Nuclear Regulatory Commission, Personnel Neutron Dosimetry, NRC Regulatory Guide 8.14, Rev. 1 (1977).

32. American National Standards Institute, Criteria for Testing Personnel Dosimeter Performance, ANSI N 13.11 (January 1983).

33. National Council on Radiation Protection and Measurements, "Protection Against Neutron Radiation," NCRP Report Number 38 (1971).

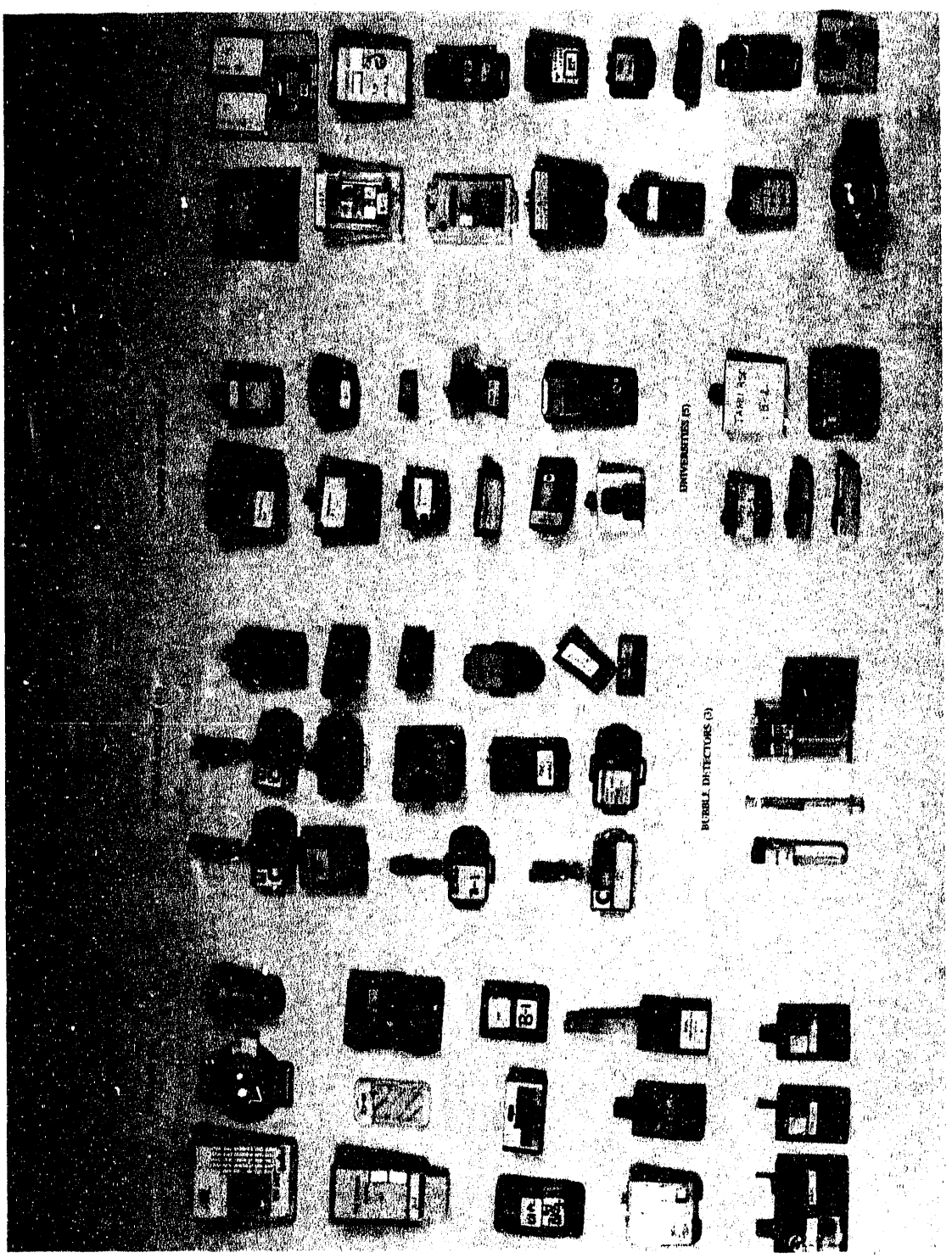


Fig. 1. Dosimeter types used in PDIS 14.

ORNL-PHOTO 2933-89

Fig. 2. Experimental setup for cadmium-covered, D_2O-moderated ^{252}Cf irradiations (this particular photograph is for exposure number 3).

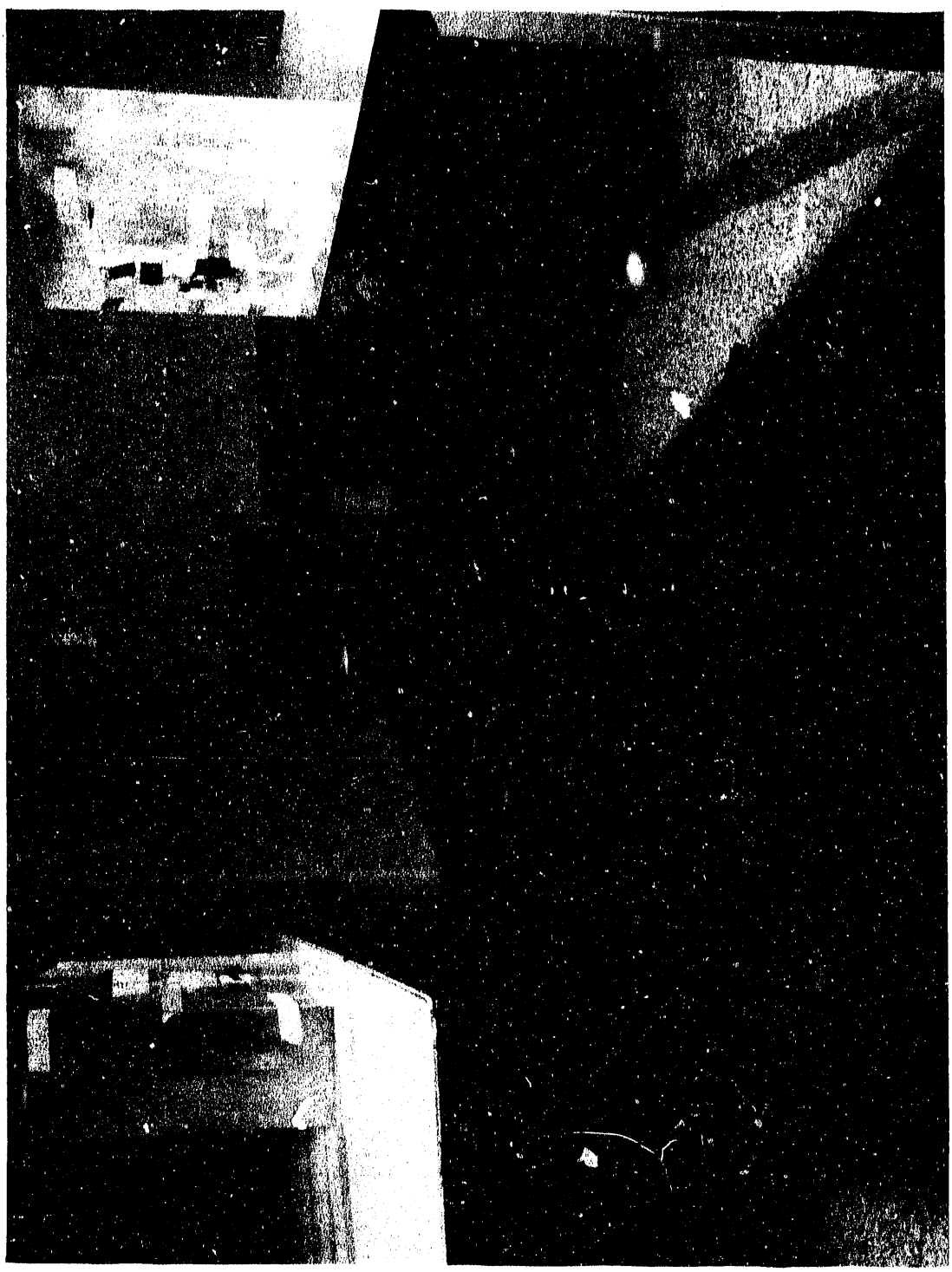
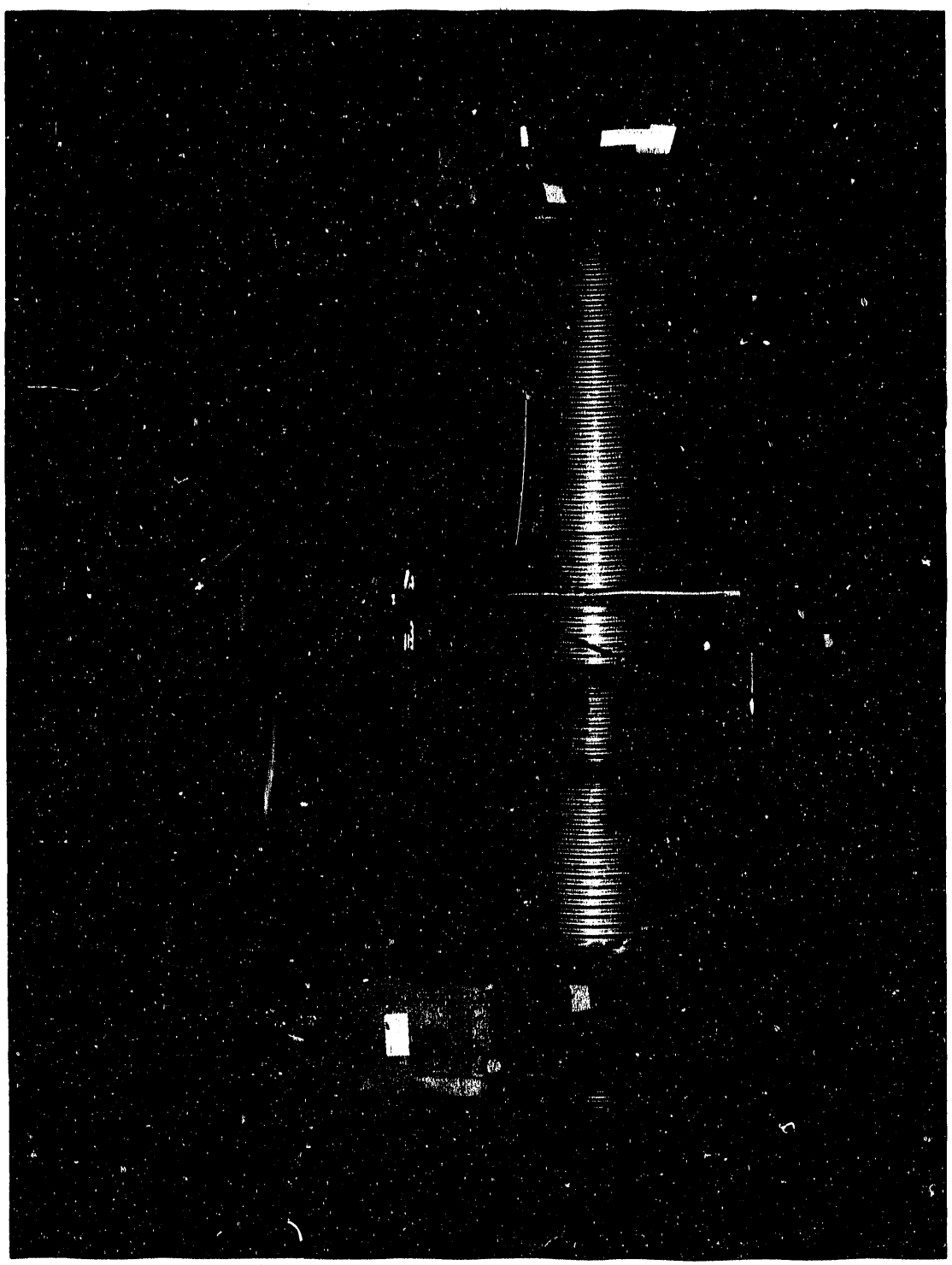


Fig. 3. ^{137}Cs irradiation configuration used as part of exposure number 2.



ORNL-PHOTO 2932-89

Fig. 4. Experimental arrangement for ^{238}PuBe exposures.

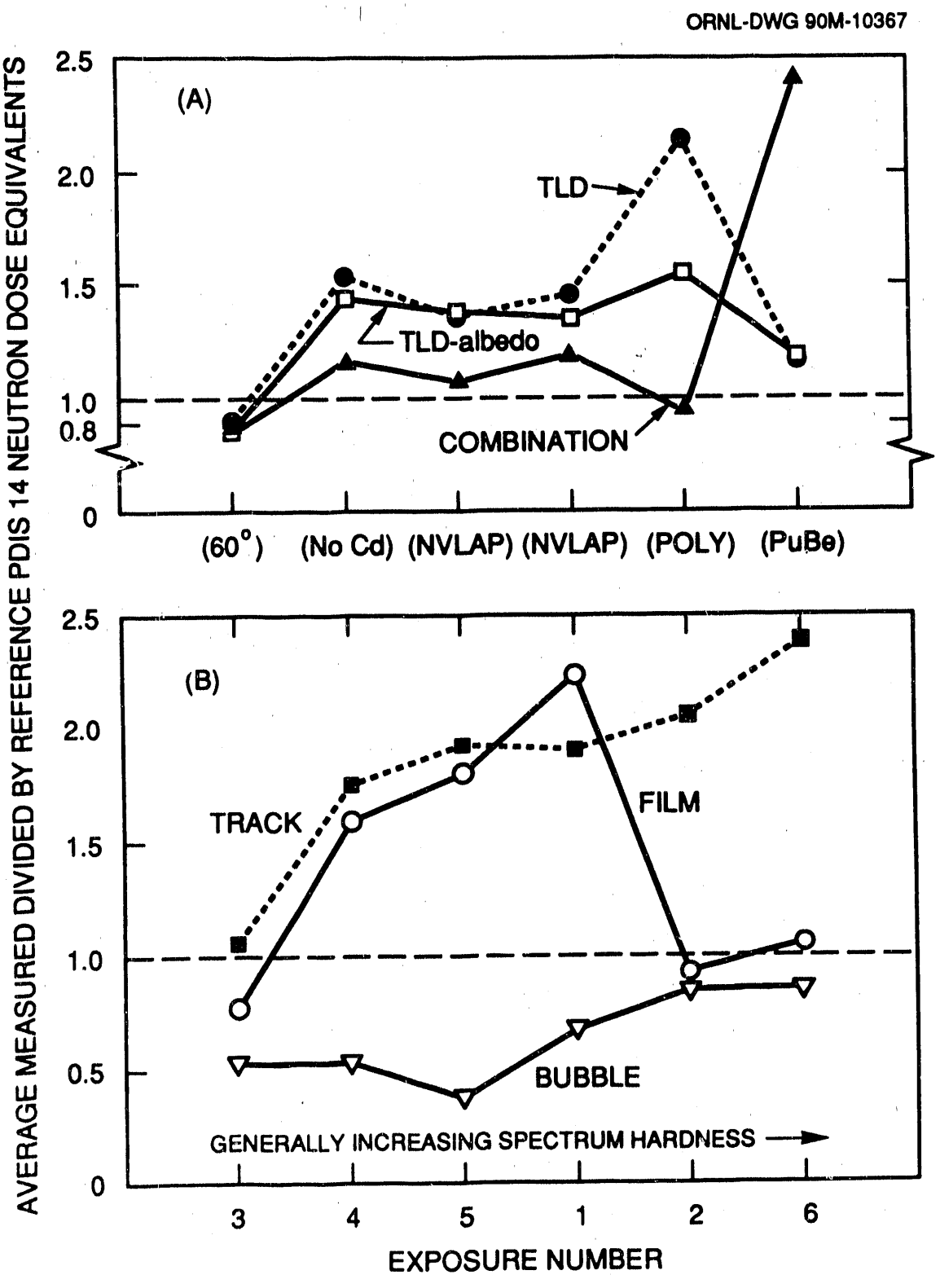


Fig. 5. Average measured neutron dose equivalents presented by type of dosimeter.

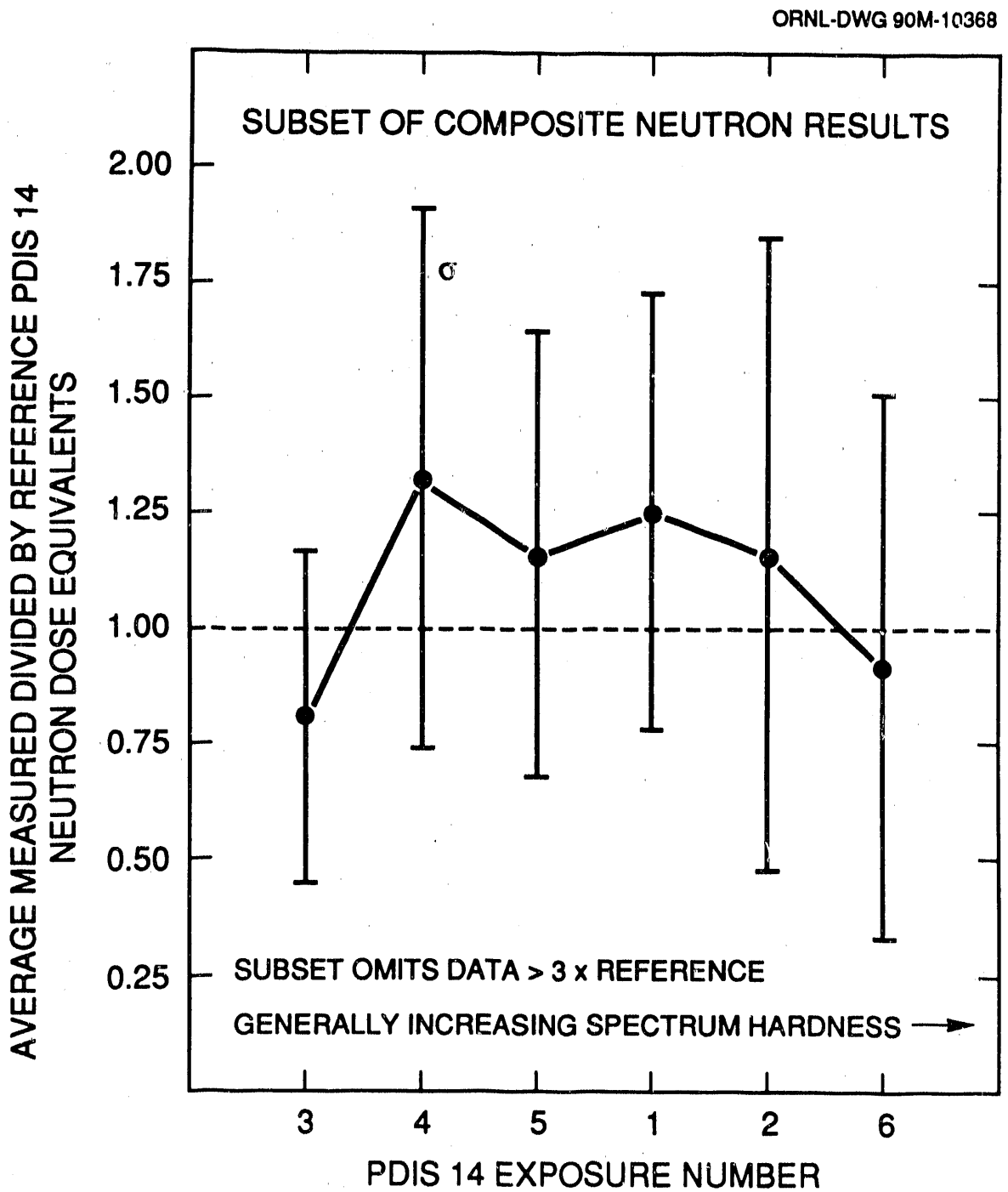


Fig. 6. Average measured neutron dose equivalents in PDIS 14.

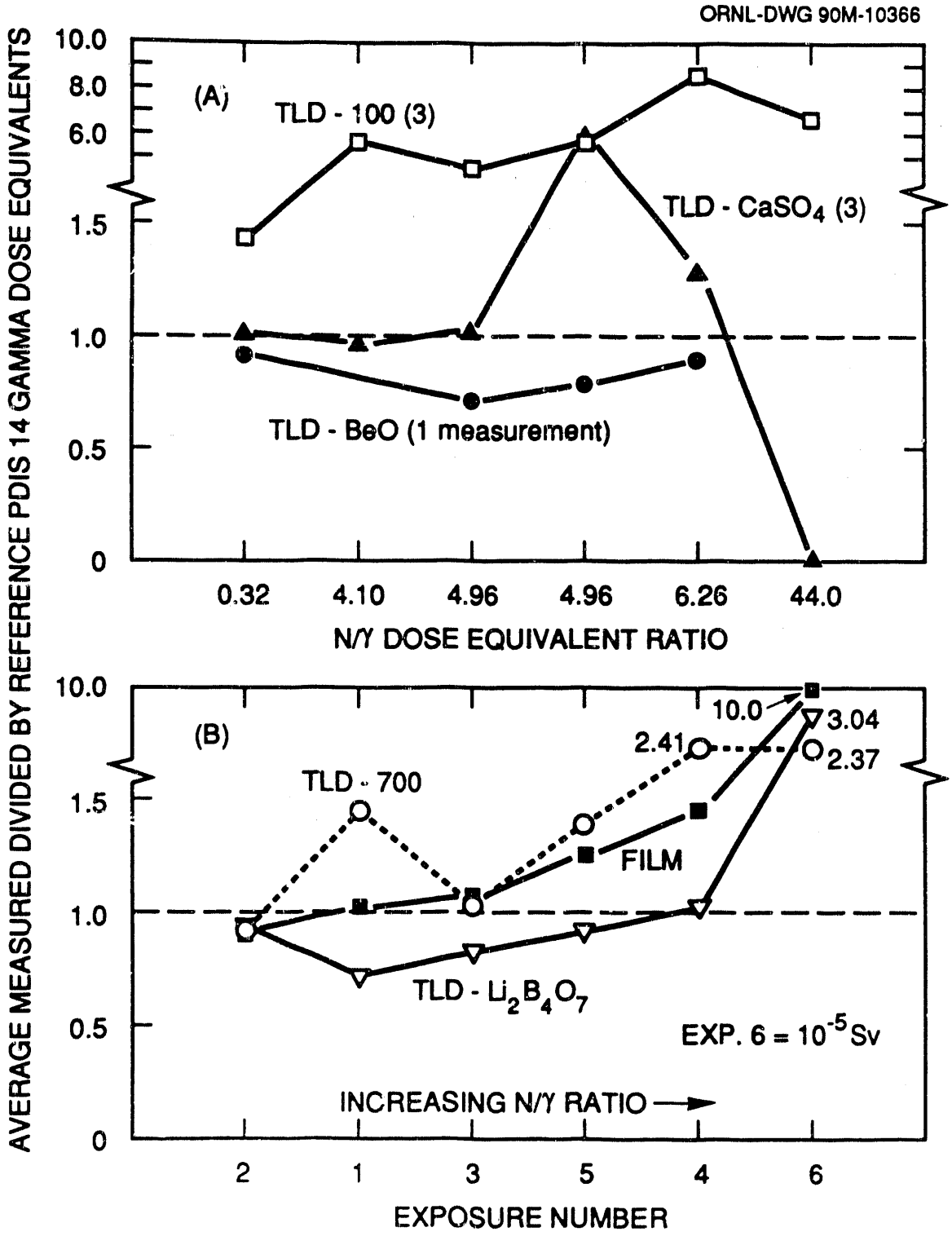


Fig. 7. Average measured gamma dose equivalents presented by type of dosimeter.

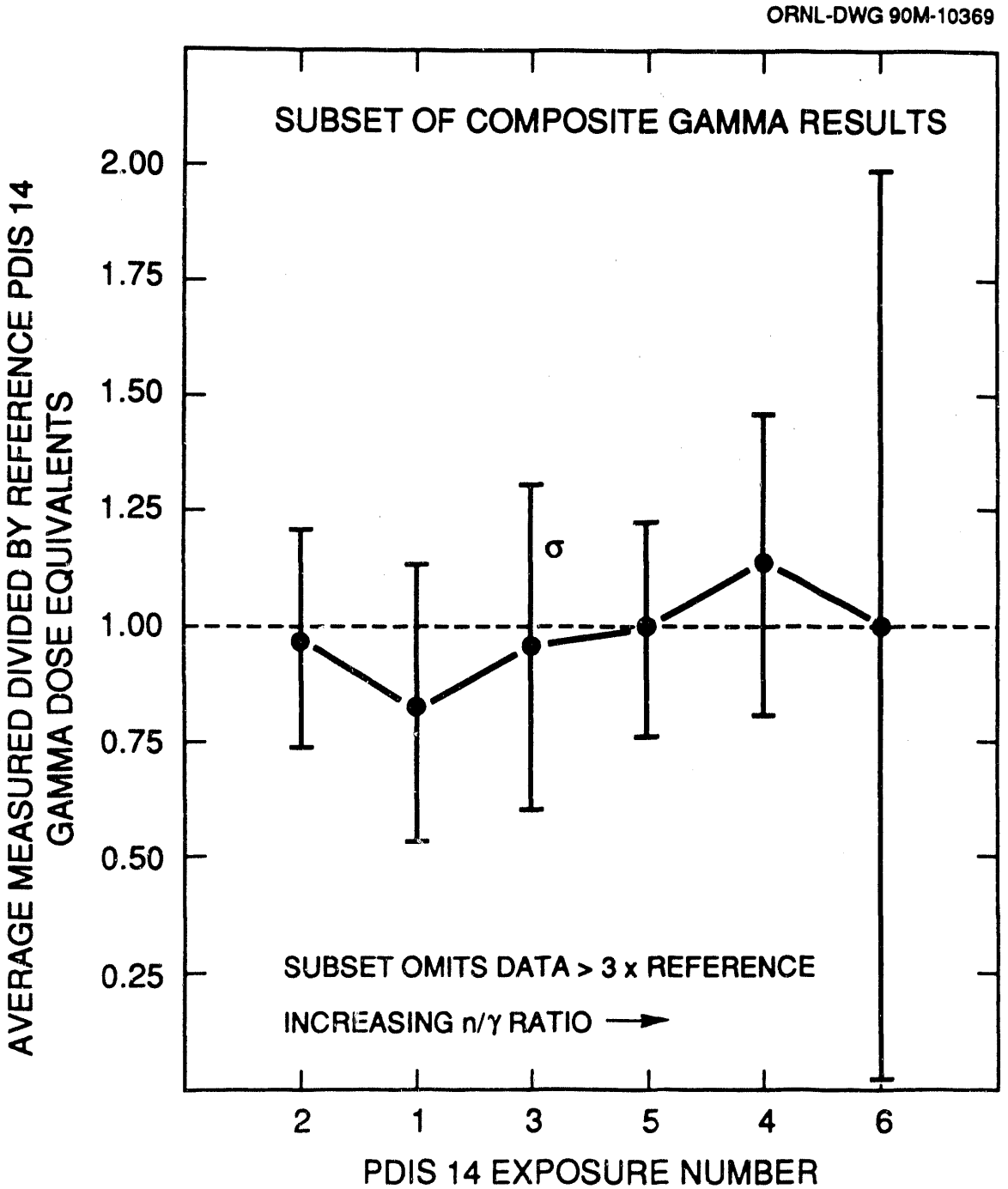


Fig. 8. Average measured gamma dose equivalents in PDIS 14.

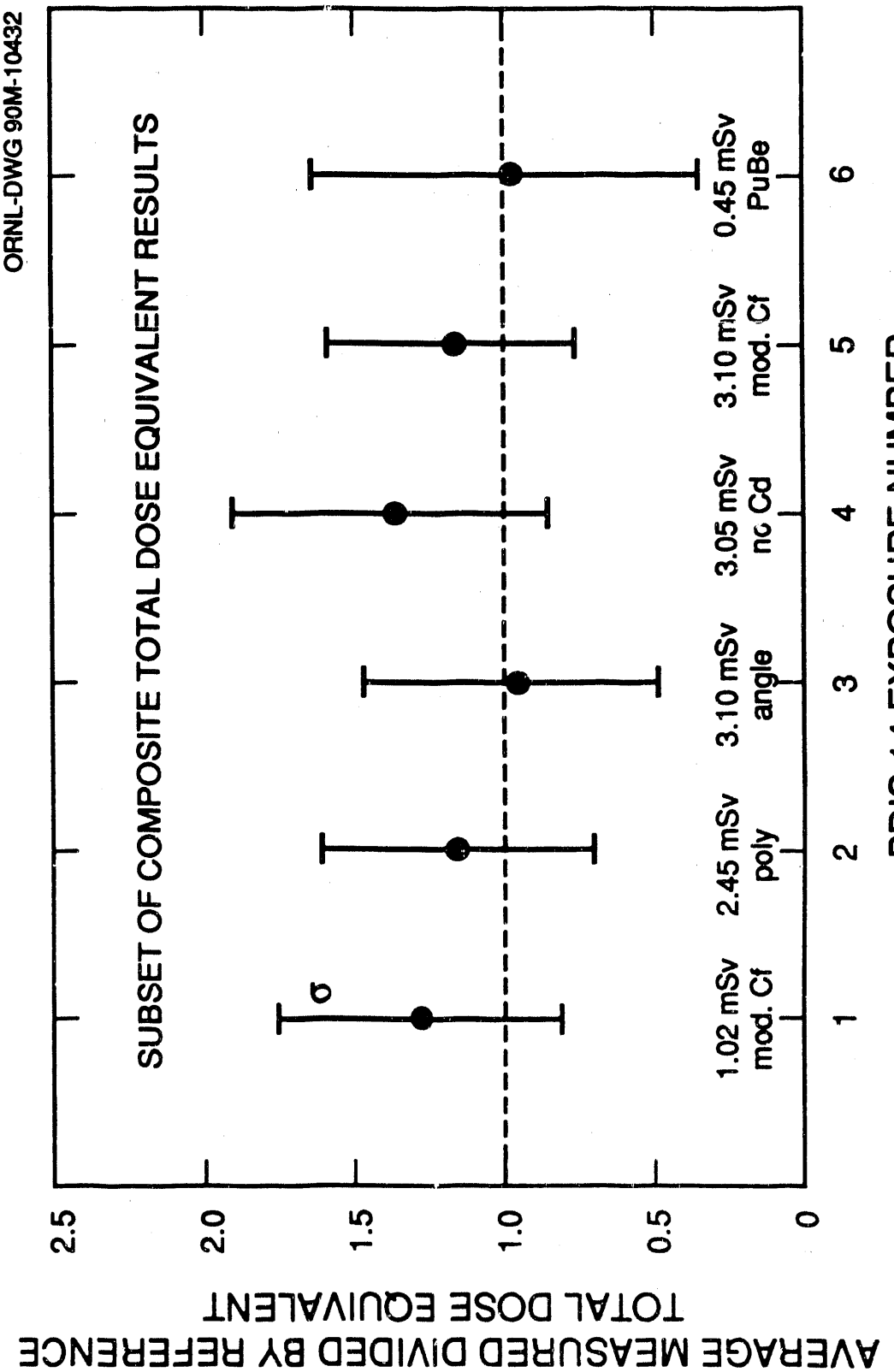


Fig. 9. Average measured total dose equivalent in PDIS 14.

Table 1. Radiation exposure conditions for PDIS 14

Exposure Number	Source Description	Distance (meters)	Date(s)	9/3" Ratio	Avg. Neutron E (Mev)
1	15-cm D_2O-moderated ^{252}Cf	1.5	5/2/89	0.26	0.55
2	^{252}Cf moderated by 15-cm polyethylene enhanced by gammas from ^{137}Cs	1.0 0.51	5/1/89 5/1/89	0.74	0.86
3	D_2O-moderated ^{252}Cf rotated 60° clockwise about vertical centerline	0.75	5/2-4/89	0.29	0.55
4	D_2O-moderated ^{252}Cf without the cadmium cover on the sphere	0.75	5/3/89	0.30	<0.55
5	15-cm D_2O-moderated ^{252}Cf	0.75	5.2-3/89	0.29	0.55
6	$^{238}PuBe$, unmoderated	1.0	5/1-4/89	3.06	4.00

The distance shown in the above table is measured from the centerline of the source to the leading edge (i.e., surface nearest the source) of the phantom.

The ^{252}Cf irradiations were performed with the centerline of the source and the phantom at 1.83 m above the floor. This was 1.38 m for the $^{238}PuBe$ irradiations.

All exposure times were 20 minutes or less except for number 6 which was 105 minutes.

Table 2. PDIS 14 reference dosimetry[a]

Exposure Number	H_{npo} (10^{-5}Sv)	Scatter component[b], room + air (%)	H_n (10^{-5}Sv)	H_g[c] (10^{-5}Sv)	$H_t = H_n + H_g$ (10^{-5}Sv)
1	69	19	82	20	102
2	56	8	60	185[d]	245
3[e]	246	5	258	52	310
4[f]	250	5	263	42	305
5	246	5	258	52	310
6	42	5	44	1	45

10^{-5}Sv = 1 mrem.
H_{npo} = neutron dose equivalent due to primary beam only.
H_n = scatter adjusted neutron dose equivalent (the real answer).
H_g = gamma dose equivalent.
H_t = total dose equivalent.

Notes: a. Reference values for the primary neutron beam were generally determined from NIST calibration of the sources and application of ICRP21 fluence-to-dose equivalent conversion factors. Exposure 2 values were determined from Bonner sphere measurements.

b. Scatter corrections were made using formulas advocated by NIST.

c. Reference gamma dose equivalents were generally measured with a Philips No. 18509 GM counter.

d. 147 mrem from ^{137}Cs + 38 mrem from the moderated ^{252}Cf.

e. Dose equivalent at perpendicular incidence.

f. The neutron fluence is 11% smaller with the cadmium cover in place than it is without it, but the dose equivalent difference is only about 1.5%. (That's the difference in H_n between exposures 4 and 5.)

Table 3. Summary of reported neutron results for PDIS 14, exposure 1, 15-cm D_2O-moderated ^{252}Cf, H_n = 82(10^{-5})Sv

Group[a]	Neutron dosimeter type	Neutron dose equivalent[b], 10^{-5}Sv[c]			
		1	2	3	Average
1	-	-	-	-	-
2	Bubble	45	-	-	45
3	TLD-albedo	359	282	323	321
4	TLD-albedo	130	140	140	137
5	TLD	115	117	123	118
6	Film, Track	220	260	-	240
7	TLD	129	137	133	133
8	Track	770	690	560	673
9	TLD	120	135	130	128
10	TLD-albedo	107	105	107	106
11	Track	60	80	70	70
12	TLD-albedo	62	55	61	59
13	Film	280	250	240	257
14A	TLD	98	-	-	98
14B	TLD-albedo	81	-	-	81
14C	Track	64	-	-	64
14D	Track	85	-	-	85
16	TLD-albedo	76	77	82	78
17	TLD-albedo & Track	120	110	100	110
18	Track	75	77	83	78
19	TLD	111	132	120	121
20	Track	136	138	142	139
21	Bubble	76	-	58	67
22	TLD-albedo	77	90	84	84
23	Track	77	103	84	88
24	-	-	-	-	-
25A	TLD	99	106	99	101
25B	TLD-albedo	101	100	104	102
25C	TLD-albedo	71	72	67	70
26	Bubble & TLD-albedo	120	103	124	116
28	TLD-albedo	105	92	96	98
31	-	-	-	-	-
33	Film	50	-	70	60
34	TLD	-	-	-	-
35	Track	70	70	70	70
37	TLD-albedo	71	56	50	59
38	TLD	97	97	103	99
39	TLD-albedo	85	87	86	86
40	TLD-albedo	102	134	103	113
41A	Film	-	-	-	-
41B	Track & TLD-albedo	-	70	-	70
41C	TLD	-	-	-	-
42A	TLD	136	150	207	164
42B	TLD-albedo	103	111	103	105
43	TLD	109	111	119	113
44	TLD-albedo	90	80	70	80
45	TLD-albedo	79	84	79	81
46	TLD-albedo	235	225	205	222
48A	TLD-albedo	122	124	108	118
48B	TLD-albedo	132	138	141	137

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 4. Summary of reported neutron results for PDIS 14, exposure 2, 15-cm polyethylene-moderated ^{252}Cf (^{137}Cs enhanced), $H_n = 60(10^{-5})Sv$

Group[a]	Neutron dosimeter type	Neutron dose equivalent[b], 10^{-5}Sv[c]			
		1	2	3	Average
1	-	-	-	-	-
2	Bubble	51	-	-	51
3	TLD-albedo	-	361	-	361
4	TLD-albedo	220	160	250	210
5	TLD	234	195	225	218
6	Film, Track	90	70	-	80
7	TLD	187	184	193	188
8	Track	690	480	480	550
9	TLD	88	78	84	83
10	TLD-albedo	162	173	189	175
11	Track	50	50	50	50
12	TLD-albedo	34	47	45	42
13	Film	-	90	90	90
14A	TLD	60	-	-	60
14B	TLD-albedo	44	-	-	44
14C	Track	43	-	-	43
14D	Track	57	-	-	57
16	TLD-albedo	94	95	105	98
17	TLD-albedo & Track	50	40	40	43
18	Track	57	60	61	59
19	TLD	154	156	159	156
20	Track	101	100	99	100
21	Bubble	54	51	50	52
22	TLD-albedo	-	3	3	2
23	Track	76	87	83	82
24	-	-	-	-	-
25A	TLD	73	66	67	69
25B	TLD-albedo	58	54	55	56
25C	TLD-albedo	38	52	46	45
26	Bubble & TLD-albedo	64	73	73	70
28	TLD-albedo	176	87	129	131
31	-	-	-	-	-
33	Film	40	-	-	40
34	TLD	-	-	-	-
35	Track	50	60	60	57
37	TLD-albedo	4	0	2	2
38	TLD	192	168	134	165
39	TLD-albedo	67	62	42	57
40	TLD-albedo	89	100	127	105
41A	Film	20	-	-	20
41B	Track & TLD-albedo	-	-	-	-
41C	TLD	-	-	-	-
42A	TLD	104	119	160	128
42B	TLD-albedo	30	26	33	30
43	TLD	107	103	90	100
44	TLD-albedo	20	30	0	17
45	TLD-albedo	245	204	231	227
46	TLD-albedo	60	60	30	50
48A	TLD-albedo	35	42	46	41
48B	TLD-albedo	100	100	96	99

[a]Participants designated by numbers to preserve anonymity
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 5. Summary of reported neutron results for PDIS 14, exposure 3, 15-cm D_2O-moderated ^{252}Cf, 60° rotation, perpendicular H_n = 258(10^{-5})Sv

Group[a]	Neutron dosimeter type	Neutron dose equivalent[b], 10^{-5}Sv[c]			
		1	2	3	Average
1	-	-	-	-	-
2	Bubble	183	-	-	183
3	TLD-albedo	576	414	424	471
4	TLD-albedo	240	240	260	247
5	TLD	182	195	198	192
6	Film, Track	220	230	-	225
7	TLD	258	252	234	248
8	Track	850	860	960	890
9	TLD	232	195	204	210
10	TLD-albedo	196	180	190	189
11	Track	90	80	100	90
12	TLD-albedo	177	152	167	165
13	Film	350	370	320	347
14A	TLD	276	-	-	276
14B	TLD-albedo	160	-	-	160
14C	Track	88	-	-	88
14D	Track	109	-	-	109
16	TLD-albedo	165	167	172	168
17	TLD-albedo & Track	260	260	260	260
18	Track	85	87	82	85
19	TLD	196	215	184	198
20	Track	454	460	521	478
21	Bubble	93	87	93	91
22	TLD-albedo	154	150	144	149
23	Track	189	175	224	196
24	-	-	-	-	-
25A	TLD	185	180	182	182
25B	TLD-albedo	202	204	200	202
25C	TLD-albedo	129	143	137	136
26	Bubble & TLD-albedo	278	279	255	271
28	TLD-albedo	202	205	187	198
31	-	-	-	-	-
33	Film	-	130	190	160
34	TLD	-	-	-	-
35	Track	280	260	240	260
37	TLD-albedo	130	148	190	156
38	TLD	182	198	175	185
39	TLD-albedo	112	249	179	180
40	TLD-albedo	168	187	185	180
41A	Film	70	-	-	70
41B	Track & TLD-albedo	-	130	-	130
41C	TLD	-	-	-	-
42A	TLD	285	301	276	287
42B	TLD-albedo	248	240	278	255
43	TLD	283	-	291	287
44	TLD-albedo	180	180	150	170
45	TLD-albedo	166	152	158	159
46	TLD-albedo	495	590	360	482
48A	TLD-albedo	213	245	239	232
48B	TLD-albedo	264	208	238	237

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 6. Summary of reported neutron results for PDIS 14, exposure 4, 15-cm D_2O-moderated ^{252}Cf, without cadmium cover on sphere, H_n = 263(10^{-5})Sv

Group[a]	Neutron dosimeter type	Neutron dose equivalent[b], 10^{-5}Sv[c]			
		1	2	3	Average
1	-	-	-	-	-
2	Bubble	181	-	-	181
3	TLD-albedo	674	545	552	590
4	TLD-albedo	510	540	600	550
5	TLD	322	331	302	318
6	Film, Track	880	900	-	890
7	TLD	518	509	551	526
8	Track	1480	1570	2080	1710
9	TLD	440	417	450	436
10	TLD-albedo	460	414	408	427
11	Track	200	250	190	213
12	TLD-albedo	267	204	242	238
13	Film	640	620	650	637
14A	TLD	286	-	-	286
14B	TLD-albedo	217	-	-	217
14C	Track	216	-	-	216
14D	Track	288	-	-	288
16	TLD-albedo	321	338	350	336
17	TLD-albedo & Track	380	360	380	373
18	Track	254	241	231	242
19	TLD	274	301	271	282
20	Track	455	460	479	465
21	Bubble	95	99	101	98
22	TLD-albedo	277	244	290	270
23	Track	312	327	366	335
24	-	-	-	-	-
25A	TLD	392	394	377	388
25B	TLD-albedo	401	349	388	379
25C	TLD-albedo	175	176	182	178
26	Bubble & TLD-albedo	312	303	318	311
28	TLD-albedo	412	284	290	329
31	-	-	-	-	-
33	Film	150	140	100	130
34	TLD	-	-	-	-
35	Track	290	170	290	250
37	TLD-albedo	479	716	588	594
38	TLD	414	472	443	443
39	TLD-albedo	271	265	272	269
40	TLD-albedo	314	390	392	365
41A	Film	40	-	-	40
41B	Track & TLD-albedo	-	250	-	250
41C	TLD	-	-	-	-
42A	TLD	727	570	673	657
42B	TLD-albedo	353	361	335	350
43	TLD	296	301	298	298
44	TLD-albedo	240	250	220	237
45	TLD-albedo	409	412	394	405
46	TLD-albedo	840	700	820	787
48A	TLD-albedo	350	362	378	363
48B	TLD-albedo	584	505	517	535

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 7. Summary of reported neutron results for PDIS 14, exposure 5, 15-cm D_2O-moderated ^{252}Cf, H_n = 258(10^{-5})Sv

Group[a]	Neutron dosimeter type	Neutron dose equivalent[b], 10^{-5}Sv[c]			
		1	2	3	Average
1	-	-	-	-	-
2	Bubble	89	-	-	89
3	TLD-albedo	1399	978	1050	1142
4	TLD-albedo	410	360	390	387
5	TLD	303	283	293	293
6	Film, Track	920	990	-	955
7	TLD	359	353	343	352
8	Track	2030	2210	2010	2083
9	TLD	357	306	326	330
10	TLD-albedo	383	335	382	367
11	Track	200	200	190	197
12	TLD-albedo	221	191	235	216
13	Film	710	630	660	667
14A	TLD	269	-	-	269
14B	TLD-albedo	273	-	-	273
14C	Track	208	-	-	208
14D	Track	266	-	-	266
16	TLD-albedo	298	279	267	281
17	TLD-albedo & Track	320	320	340	327
18	Track	220	200	219	213
19	TLD	376	359	288	341
20	Track	466	505	401	457
21	Bubble	117	118	85	107
22	TLD-albedo	258	248	255	254
23	Track	365	297	298	320
24	-	-	-	-	-
25A	TLD	301	334	304	313
25B	TLD-albedo	283	283	295	287
25C	TLD-albedo	190	190	192	191
26	Bubble & TLD-albedo	351	304	337	331
28	TLD-albedo	283	286	326	298
31	-	-	-	-	-
33	Film	160	160	130	150
34	TLD	187	494	676	452
35	Track	300	260	300	287
37	TLD-albedo	158	223	207	196
38	TLD	272	323	337	311
39	TLD-albedo	226	236	257	240
40	TLD-albedo	349	352	298	333
41A	Film	90	-	-	90
41B	Track & TLD-albedo	-	170	-	170
41C	TLD	-	-	-	-
42A	TLD	440	578	432	484
42B	TLD-albedo	311	331	312	318
43	TLD	297	328	313	313
44	TLD-albedo	250	310	220	260
45	TLD-albedo	248	224	227	233
46	TLD-albedo	590	770	810	723
48A	TLD-albedo	311	311	289	304
48B	TLD-albedo	387	359	394	380

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 8. Summary of reported neutron results for PDIS 14, exposure 6, $^{238}PuBe$, $H_n = 44(10^{-5})Sv$

Group[a]	Neutron dosimeter type	Neutron dose equivalent[b], $10^{-5}Sv$[c]			
		1	2	3	Average
1	-	-	-	-	-
2	Bubble	39	-	-	39
3	TLD-albedo	17	46	30	31
4	TLD-albedo	74	87	52	71
5	TLD	115	76	130	107
6	Film, Track	44	41	-	43
7	TLD	33	57	54	48
8	Track	340	630	590	520
9	TLD	78	78	116	91
10	TLD-albedo	67	40	80	62
11	Track	50	30	30	37
12	TLD-albedo	54	63	72	63
13	Film	-	60	60	60
14A	TLD	61	-	-	61
14B	TLD-albedo	35	-	-	35
14C	Track	42	-	-	42
14D	Track	39	-	-	39
16	TLD-albedo	61	71	76	69
17	TLD-albedo & Track	40	40	40	40
18	Track	55	54	55	55
19	TLD	19	24	28	24
20	Track	50	48	43	47
21	Bubble	37	34	37	36
22	TLD-albedo	0	0	0	0
23	Track	58	50	48	52
24	-	-	-	-	-
25A	TLD	34	36	33	34
25B	TLD-albedo	35	37	38	37
25C	TLD-albedo	57	50	-	54
26	Bubble & TLD-albedo	54	44	53	50
28	TLD-albedo	38	37	-	38
31	-	-	-	-	-
33	Film	0	0	0	0
34	TLD	0.52	0.39	0.44	0.45
35	Track	50	60	60	57
37	TLD-albedo	0	0	0	0
38	TLD	49	14	79	47
39	TLD-albedo	80	48	64	64
40	TLD-albedo	339	211	281	277
41A	Film	40	-	-	40
41B	Track & TLD-albedo	-	230	-	230
41C	TLD	-	-	-	-
42A	TLD	0	0	0	0
42B	TLD-albedo	0	0	0	0
43	TLD	113	39	74	75
44	TLD-albedo	0	0	0	0
45	TLD-albedo	130	167	149	149
46	TLD-albedo	10	20	10	13
48A	TLD-albedo	0	0	0	0
48B	TLD-albedo	0	0	0	0

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 9. Analysis of reported neutron results for exposure 1, 15-cm D_2O-moderated ^{252}Cf, $H_n = 82(10^{-5})Sv$

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	44	0.55 - 8.21	1.51 ± 1.22
Subset[b]	41	0.55 - 2.93	1.25 ± 0.48
TLD	9	1.20 - 2.00	1.46 ± 0.24
TLD-albedo	19	0.72 - 3.92	1.37 ± 0.74
Track	8	0.78 - 8.21	1.93 ± 2.39
Film	3	0.73 - 3.13	2.26 ± 1.09
Bubble	2	0.55 - 0.82	0.69 ± 0.14
Combination	3	0.85 - 1.41	1.20 ± 0.25

[a]Reported neutron dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 10. Analysis of reported neutron results for exposure 2, 15-cm polyethylene moderated ^{252}Cf (^{137}Cs enhanced), $H_n = 60(10^{-5})Sv$

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	44	0.03 - 9.17	1.67 ± 1.63
Subset[b]	38	0.03 - 2.91	1.16 ± 0.68
TLD	9	1.00 - 3.63	2.16 ± 0.87
TLD-albedo	19	0.03 - 6.02	1.57 ± 1.49
Track	8	0.72 - 9.17	2.08 ± 2.70
Film	4	0.33 - 1.50	0.96 ± 0.48
Bubble	2	0.85 - 0.86	0.86 ± 0.01
Combination	2	0.72 - 1.17	0.95 ± 0.23

[a]Reported neutron dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 11. Analysis of reported neutron results for exposure 3, 15-cm D_2O-moderated ^{252}Cf, 60° rotation, perpendicular $H_n = 258(10^{-5})Sv$

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	45	0.27 - 3.45	0.87 ± 0.53
Subset[b]	44	0.27 - 1.87	0.81 ± 0.36
TLD	9	0.71 - 1.11	0.89 ± 0.16
TLD-albedo	19	0.53 - 1.87	0.84 ± 0.37
Track	8	0.33 - 3.45	1.06 ± 1.02
Film	4	0.27 - 1.34	0.78 ± 0.39
Bubble	2	0.35 - 0.71	0.53 ± 0.18
Combination	3	0.50 - 1.05	0.85 ± 0.25

[a]Reported neutron dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 12. Analysis of reported neutron results for exposure 4, 15-cm D_2O-moderated ^{252}Cf, without cadmium cover on sphere, $H_n = 263(10^{-5})Sv$

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	45	0.15 - 6.50	1.49 ± 1.00
Subset[b]	43	0.15 - 2.99	1.33 ± 0.59
TLD	9	1.07 - 2.50	1.53 ± 0.46
TLD-albedo	19	0.68 - 2.99	1.48 ± 0.58
Track	8	0.81 - 6.50	1.77 ± 1.81
Film	4	0.15 - 3.38	1.61 ± 1.34
Bubble	2	0.37 - 0.69	0.53 ± 0.16
Combination	3	0.95 - 1.42	1.18 ± 0.19

[a]Reported neutron dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 13. Analysis of reported neutron results for exposure 5, 15-cm D_2O-moderated ^{252}Cf, $H_n = 258(10^{-5})Sv$

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	46	0.34 - 8.07	1.44 ± 1.24
Subset[b]	43	0.34 - 2.80	1.16 ± 0.48
TLD	10	1.04 - 1.87	1.34 ± 0.25
TLD-albedo	19	0.74 - 4.43	1.36 ± 0.84
Track	8	0.76 - 8.07	1.95 ± 2.33
Film	4	0.35 - 3.70	1.80 ± 1.40
Bubble	2	0.34 - 0.41	0.38 ± 0.03
Combination	3	0.66 - 1.28	1.07 ± 0.29

[a]Reported neutron dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 14. Analysis of reported neutron results for exposure 6, $^{238}PuBe$, $H_n = 44(10^{-5})Sv$

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	45	0.00 - 11.82	1.43 ± 1.97
Subset[b]	41	0.00 - 2.43	0.92 ± 0.59
TLD	10	0.00 - 2.43	1.11 ± 0.77
TLD-albedo	19	0.00 - 6.30	1.15 ± 1.47
Track	8	0.83 - 11.82	2.41 ± 3.56
Film	3	0.91 - 1.36	1.08 ± 0.20
Bubble	2	0.82 - 0.89	0.86 ± 0.03
Combination	3	0.91 - 5.23	2.43 ± 1.98

[a]Reported neutron dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 15. Summary of reported gamma results for PDIS 14, exposure 1, 15-cm D_2O-moderated ^{252}Cf, $H_g = 20(10^{-5})Sv$

Group[a]	Gamma dosimeter type	Gamma dose equivalent[b], 10^{-5}Sv[c]			
		1	2	3	Average
1	TLD-700	72	78	70	73
2	-	-	-	-	-
3	TLD-$Li_2B_4O_7$	14	17	16	16
4	TLD-$Li_2B_4O_7$	15	16	13	15
5	TLD-$Li_2B_4O_7$	13	13	13	13
6	Film	23	22	20	22
7	TLD-$Li_2B_4O_7$	14	15	14	14
8	TLD-BeO	0	0	0	0
9	TLD-$Li_2B_4O_7$	13	12	12	12
10	TLD-$Li_2B_4O_7$	12	12	11	12
11	TLD-100	300	300	280	293
12	TLD-700	14	10	11	12
13	Film	20	20	30	23
14A	TLD-700	21	-	-	21
14B	TLD-700	18	-	-	18
14C	-	-	-	-	-
14D	-	-	-	-	-
16	TLD-700	14	11	13	13
17	Film	30	30	20	27
18	TLD-$Li_2B_4O_7$	21	16	12	16
19	TLD-$Li_2B_4O_7$	12	16	15	14
20	Film	19	19	19	19
21	-	-	-	-	-
22	TLD-$Li_2B_4O_7$	14	14	15	14
23	-	-	-	-	-
24	TLD-700	9	8	23	13
25A	TLD-700	18	10	12	13
25B	TLD-700	13	13	13	13
25C	TLD-$Li_2B_4O_7$	0	0	0	0
26	TLD-700	15	19	15	16
28	$Li_2B_4O_7$	19	20	14	18
31	TLD-700	9	10	10	10
33	Film	-	10	10	10
34	TLD-$CaSO_4$	18	15	18	17
35	TLD-700	30	30	30	30
37	TLD-$Li_2B_4O_7$	0	16	18	11
38	TLD-$Li_2B_4O_7$	10	9	18	12
39	TLD-700	14	14	15	14
40	TLD-$CaSO_4$	27	22	22	24
41A	Film	20	-	-	20
41B	-	-	-	-	-
41C	TLD-700	-	-	150	150
42A	TLD-100	43	31	18	31
42B	TLD-100	19	26	20	22
43	TLD-$Li_2B_4O_7$	22	18	15	18
44	TLD-700	10	10	10	10
45	TLD-$CaSO_4$	20	17	15	17
46	TLD-$Li_2B_4O_7$	15	15	15	15
48A	TLD-$Li_2B_4O_7$	38	21	30	30
48B	TLD-$Li_2B_4O_7$	0	0	0	0

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 16. Summary of reported gamma results for PDIS 14, exposure 2, 15-cm polyethylene moderated ^{252}Cf (^{137}Cs enhanced), H_g = 185(10^{-5})Sv

Group[a]	Gamma dosimeter type	Gamma dose equivalent[b], 10^{-5}Sv[c]			
		1	2	3	Average
1	TLD-700	165	169	170	168
2	-	-	-	-	-
3	TLD-$Li_2B_4O_7$	175	199	198	191
4	TLD-$Li_2B_4O_7$	180	200	180	187
5	TLD-$Li_2B_4O_7$	175	181	181	179
6	Film	190	190	190	190
7	TLD-$Li_2B_4O_7$	184	187	188	186
8	TLD-BeO	175	159	175	170
9	TLD-$Li_2B_4O_7$	174	171	167	171
10	TLD-$Li_2B_4O_7$	159	155	154	156
11	TLD-100	410	440	450	433
12	TLD-700	162	152	161	158
13	Film	190	200	190	193
14A	TLD-700	197	-	-	197
14B	TLD-700	187	-	-	187
14C	-	-	-	-	-
14D	-	-	-	-	-
16	TLD-700	194	190	169	184
17	Film	160	150	160	157
18	TLD-$Li_2B_4O_7$	155	173	163	164
19	TLD-$Li_2B_4O_7$	180	176	185	180
20	Film	174	174	180	176
21	-	-	-	-	-
22	TLD-$Li_2B_4O_7$	179	174	173	175
23	-	-	-	-	-
24	TLD-700	119	117	117	118
25A	TLD-700	137	133	135	135
25B	TLD-700	148	144	141	144
25C	TLD-$Li_2B_4O_7$	159	160	159	159
26	TLD-700	163	163	159	162
28	$Li_2B_4O_7$	210	206	222	213
31	TLD-700	138	134	132	135
33	Film	180	190	180	183
34	TLD-$CaSO_4$	196	197	194	196
35	TLD-700	200	185	180	188
37	TLD-$Li_2B_4O_7$	223	188	152	188
38	TLD-$Li_2B_4O_7$	171	169	175	172
39	TLD-700	165	165	173	168
40	TLD-$CaSO_4$	206	199	211	205
41A	Film	160	-	-	160
41B	-	-	-	-	-
41C	TLD-700	-	-	270	270
42A	TLD-100	202	184	234	207
42B	TLD-100	157	183	163	168
43	TLD-$Li_2B_4O_7$	192	194	182	189
44	TLD-700	150	170	170	163
45	TLD-$CaSO_4$	163	155	160	159
46	TLD-$Li_2B_4O_7$	170	145	155	157
48A	TLD-$Li_2B_4O_7$	193	177	166	179
48B	TLD-$Li_2B_4O_7$	173	179	176	176

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 17. Summary of reported gamma results for PDIS 14, exposure 3, 15-cm D_2O-moderated ^{252}Cf, 60° rotation, perpendicular H_g = 52(10^{-5})Sv

Group[a]	Gamma dosimeter type	Gamma dose equivalent[b], 10^{-5}Sv[c]			
		1	2	3	Average
1	TLD-700	140	139	-	140
2	-	-	-	-	-
3	TLD-$Li_2B_4O_7$	42	49	48	46
4	TLD-$Li_2B_4O_7$	49	44	40	44
5	TLD-$Li_2B_4O_7$	43	41	32	39
6	Film	58	57	55	57
7	TLD-$Li_2B_4O_7$	45	44	42	44
8	TLD-BeO	43	40	28	37
9	TLD-$Li_2B_4O_7$	39	48	38	42
10	TLD-$Li_2B_4O_7$	41	36	38	38
11	TLD-100	570	550	580	567
12	TLD-700	42	47	39	43
13	Film	60	60	60	60
14A	TLD-700	54	-	-	54
14B	TLD-700	49	-	-	49
14C	-	-	-	-	-
14D	-	-	-	-	-
16	TLD-700	42	49	40	44
17	Film	60	60	60	60
18	TLD-$Li_2B_4O_7$	46	33	46	42
19	TLD-$Li_2B_4O_7$	46	51	40	46
20	Film	64	64	64	64
21	-	-	-	-	-
22	TLD-$Li_2B_4O_7$	42	45	44	44
23	-	-	-	-	-
24	TLD-700	30	29	32	30
25A	TLD-700	39	38	37	38
25B	TLD-700	41	39	42	41
25C	TLD-$Li_2B_4O_7$	34	38	32	35
26	TLD-700	43	46	46	45
28	$Li_2B_4O_7$	57	60	62	60
31	TLD-700	30	30	28	29
33	Film	40	50	50	47
34	TLD-$CaSO_4$	55	55	57	56
35	TLD-700	65	65	70	67
37	TLD-$Li_2B_4O_7$	41	64	54	53
38	TLD-$Li_2B_4O_7$	45	43	41	43
39	TLD-700	41	47	42	43
40	TLD-$CaSO_4$	43	55	54	51
41A	Film	50	-	-	50
41B	-	-	-	-	-
41C	TLD-700	-	-	100	100
42A	TLD-100	47	59	93	66
42B	TLD-100	55	59	63	59
43	TLD-$Li_2B_4O_7$	45	-	47	46
44	TLD-700	50	40	40	43
45	TLD-$CaSO_4$	54	46	54	51
46	TLD-$Li_2B_4O_7$	45	35	45	42
48A	TLD-$Li_2B_4O_7$	35	36	43	38
48B	TLD-$Li_2B_4O_7$	22	34	40	32

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 18. Summary of reported gamma results for PDIS 14, exposure 4, 15-cm D_2O-moderated ^{252}Cf, without cadmium cover on sphere, H_g = 42(10^{-5})Sv

Group[a]	Gamma dosimeter type	Gamma dose equivalent[b], 10^{-5}Sv[c]			
		1	2	3	Average
1	TLD-700	261	261	256	259
2	-	-	-	-	-
3	TLD-$Li_2B_4O_7$	48	45	46	46
4	TLD-$Li_2B_4O_7$	38	38	41	39
5	TLD-$Li_2B_4O_7$	44	42	43	43
6	Film	64	62	60	62
7	TLD-$Li_2B_4O_7$	39	37	41	39
8	TLD-BeO	38	34	42	38
9	TLD-$Li_2B_4O_7$	41	36	35	37
10	TLD-$Li_2B_4O_7$	38	38	36	37
11	TLD-100	900	970	930	933
12	TLD-700	42	32	39	38
13	Film	70	70	70	70
14A	TLD-700	40	-	-	40
14B	TLD-700	47	-	-	47
14C	-	-	-	-	-
14D	-	-	-	-	-
16	TLD-700	45	41	43	43
17	Film	60	60	60	60
18	TLD-$Li_2B_4O_7$	39	41	50	43
19	TLD-$Li_2B_4O_7$	37	37	37	37
20	Film	64	64	64	64
21	-	-	-	-	-
22	TLD-$Li_2B_4O_7$	47	50	40	46
23	-	-	-	-	-
24	TLD-700	34	44	41	40
25A	TLD-700	35	38	37	37
25B	TLD-700	31	37	38	35
25C	TLD-$Li_2B_4O_7$	36	34	32	34
26	TLD-700	43	46	41	43
28	$Li_2B_4O_7$	56	58	64	59
31	TLD-700	28	25	28	27
33	Film	50	60	50	53
34	TLD-$CaSO_4$	61	54	55	57
35	TLD-700	70	85	95	83
37	TLD-$Li_2B_4O_7$	46	49	62	52
38	TLD-$Li_2B_4O_7$	35	49	34	39
39	TLD-700	41	40	41	44
40	TLD-$CaSO_4$	53	45	50	49
41A	Film	60	-	-	60
41B	-	-	-	-	-
41C	TLD-700	-	-	650	650
42A	TLD-100	54	41	159	88
42B	TLD-100	77	73	73	74
43	TLD-$Li_2B_4O_7$	46	47	43	45
44	TLD-700	30	40	40	37
45	TLD-$CaSO_4$	56	54	60	57
46	TLD-$Li_2B_4O_7$	40	20	35	32
48A	TLD-$Li_2B_4O_7$	49	39	50	46
48B	TLD-$Li_2B_4O_7$	51	55	45	50

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 19. Summary of reported gamma results for PDIS 14, exposure 5, 15-cm D_2O-moderated ^{252}Cf, H_g = 52(10^{-5})Sv

Group[a]	Gamma dosimeter type	Gamma dose equivalent[b], 10^{-5}Sv[c]			
		1	2	3	Average
1	TLD-700	42	42	43	42
2	-	-	-	-	-
3	TLD-$Li_2B_4O_7$	48	52	55	52
4	TLD-$Li_2B_4O_7$	48	46	44	46
5	TLD-$Li_2B_4O_7$	50	47	43	47
6	Film	68	68	61	66
7	TLD-$Li_2B_4O_7$	44	45	44	44
8	TLD-BeO	44	33	46	41
9	TLD-$Li_2B_4O_7$	41	42	42	42
10	TLD-$Li_2B_4O_7$	40	41	45	42
11	TLD-100	780	760	720	753
12	TLD-700	45	43	47	45
13	Film	80	70	70	73
14A	TLD-700	53	-	-	53
14B	TLD-700	44	-	-	44
14C	-	-	-	-	-
14D	-	-	-	-	-
16	TLD-700	44	44	44	44
17	Film	70	60	60	63
18	TLD-$Li_2B_4O_7$	49	52	41	47
19	TLD-$Li_2B_4O_7$	46	40	47	44
20	Film	71	77	71	73
21	-	-	-	-	-
22	TLD-$Li_2B_4O_7$	49	44	47	47
23	-	-	-	-	-
24	TLD-700	38	34	47	40
25A	TLD-700	44	47	43	45
25B	TLD-700	39	41	41	40
25C	TLD-$Li_2B_4O_7$	32	37	42	37
26	TLD-700	47	45	45	46
28	$Li_2B_4O_7$	56	67	55	59
31	TLD-700	32	32	32	32
33	Film	60	50	70	60
34	TLD-$CaSO_4$	850	806	810	822
35	TLD-700	90	80	85	85
37	TLD-$Li_2B_4O_7$	83	54	57	65
38	TLD-$Li_2B_4O_7$	42	46	51	46
39	TLD-700	48	45	47	47
40	TLD-$CaSO_4$	55	60	58	58
41A	Film	60	-	-	60
41B	-	-	-	-	-
41C	TLD-700	-	-	410	410
42A	TLD-100	73	96	64	78
42B	TLD-100	75	79	70	75
43	TLD-$Li_2B_4O_7$	53	46	46	48
44	TLD-700	40	50	40	43
45	TLD-$CaSO_4$	52	53	59	55
46	TLD-$Li_2B_4O_7$	45	45	40	43
48A	TLD-$Li_2B_4O_7$	40	66	44	50
48B	TLD-$Li_2B_4O_7$	63	55	46	55

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 20. Summary of reported gamma results for PDIS 14, exposure 6, $^{238}PuBe$, $H_g = 1(10^{-5})Sv$

Group[a]	Gamma dosimeter type	Gamma dose equivalent[b], $10^{-5}Sv$[c]			
		1	2	3	Average
1	TLD-700	5	4	5	5
2	-	-	-	-	-
3	TLD-$Li_2B_4O_7$	2	2	2	2
4	TLD-$Li_2B_4O_7$	2	2	2	2
5	TLD-$Li_2B_4O_7$	3	3	3	3
6	Film	10	10	10	10
7	TLD-$Li_2B_4O_7$	3	2	2	2
8	TLD-BeO	0	0	0	0
9	TLD-$Li_2B_4O_7$	3	2	2	2
10	TLD-$Li_2B_4O_7$	0	0	1	0
11	TLD-100	20	20	20	20
12	TLD-700	0	1	0	0
13	Film	0	0	0	0
14A	TLD-700	3	-	-	3
14B	TLD-700	2	-	-	2
14C	-	-	-	-	-
14D	-	-	-	-	-
16	TLD-700	0	0	1	0
17	Film	10	10	10	10
18	TLD-$Li_2B_4O_7$	0	0	0	0
19	TLD-$Li_2B_4O_7$	2	3	1	2
20	Film	0	0	0	0
21	-	-	-	-	-
22	TLD-$Li_2B_4O_7$	2	2	2	2
23	-	-	-	-	-
24	TLD-700	2	0	3	2
25A	TLD-700	0	0	0	0
25B	TLD-700	0	0	0	0
25C	TLD-$Li_2B_4O_7$	0	0	0	0
26	TLD-700	2	2	2	2
28	$Li_2B_4O_7$	2	3	3	3
31	TLD-700	1	1	1	1
33	Film	0	0	0	0
34	TLD-$CaSO_4$	253	247	242	247
35	TLD-700	0	0	0	0
37	TLD-$Li_2B_4O_7$	54	0	10	21
38	TLD-$Li_2B_4O_7$	6	6	0	4
39	TLD-700	1	1	2	1
40	TLD-$CaSO_4$	0	0	0	0
41A	Film	0	0	0	0
41B	-	-	-	-	-
41C	TLD-700	0	0	0	0
42A	TLD-100	0	0	0	0
42B	TLD-100	0	0	0	0
43	TLD-$Li_2B_4O_7$	4	4	6	5
44	TLD-700	10	10	10	10
45	TLD-$CaSO_4$	0	0	0	0
46	TLD-$Li_2B_4O_7$	0	0	0	0
48A	TLD-$Li_2B_4O_7$	0	0	0	0
48B	TLD-$Li_2B_4O_7$	0	0	0	0

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values as reported by participants.
[c]10^{-5} Sv = 1 mrem.

Table 21. Analysis of reported gamma results for exposure 1, 15-cm D_2O-moderated ^{252}Cf, $H_g = 20(10^{-5})Sv$

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	42	0.00 - 14.67	1.38 ± 2.36
Subset[b]	39	0.00 - 1.53	0.83 ± 0.30
TLD-100	3	1.08 - 14.67	5.76 ± 6.30
TLD-700	14	0.48 - 7.50	1.45 ± 1.85
TLD-BeO	0	0.00 - 0.00	0.00 ± 0.00
TLD-$CaSO_4$	3	0.86 - 1.18	0.97 ± 0.15
TLD-$Li_2B_4O_7$	16	0.00 - 1.48	0.72 ± 0.28
Film	6	0.50 - 1.33	1.01 ± 0.26

[a]Reported gamma dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 22. Analysis of reported gamma results for exposure 2, 15-cm polyethylene moderated ^{252}Cf, (^{137}Cs enhanced), H_g = 185(10^{-5})Sv

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	44	0.64 - 2.34	0.98 ± 0.24
Subset[b]	44	0.64 - 2.34	0.98 ± 0.24
TLD-100	3	0.91 - 2.34	1.46 ± 0.63
TLD-700	14	0.64 - 1.46	0.92 ± 0.19
TLD-BeO	1	0.92 - 0.92	0.92 ± 0.00
TLD-$CaSO_4$	3	0.86 - 1.11	1.01 ± 0.11
TLD-$Li_2B_4O_7$	17	0.84 - 1.15	0.96 ± 0.08
Film	6	0.85 - 1.05	0.96 ± 0.08

[a]Reported gamma dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 23. Analysis of reported gamma results for exposure 3, 15-cm D_2O-moderated ^{252}Cf, 60° rotation, perpendicular $H_g = 52(10^{-5})Sv$

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	44	0.56 - 10.90	1.19 ± 1.52
Subset[b]	43	0.56 - 2.68	0.96 ± 0.35
TLD-100	3	1.13 - 10.90	4.44 ± 4.57
TLD-700	14	0.56 - 2.68	1.05 ± 0.56
TLD-BeO	1	0.71 - 0.71	0.71 ± 0.00
TLD-$CaSO_4$	3	0.97 - 1.07	1.01 ± 0.04
TLD-$Li_2B_4O_7$	17	0.62 - 1.15	0.83 ± 0.12
Film	6	0.90 - 1.23	1.08 ± 0.11

[a]Reported gamma dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 24. Analysis of reported gamma results for exposure 4, 15-cm D_2O-moderated ^{252}Cf, without cadmium cover on sphere, $H_g = 42(10^{-5})Sv$

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	44	0.64 - 22.22	2.06 ± 3.82
Subset[b]	41	0.64 - 2.10	1.14 ± 0.32
TLD-100	3	1.77 - 22.22	8.70 ± 9.56
TLD-700	14	0.64 - 15.48	2.41 ± 3.87
TLD-BeO	1	0.90 - 0.90	0.90 ± 0.00
TLD-$CaSO_4$	3	1.17 - 1.35	1.29 ± 0.08
TLD-$Li_2B_4O_7$	17	0.75 - 1.41	1.02 ± 0.16
Film	6	1.27 - 1.67	1.47 ± 0.12

[a]Reported gamma dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 25. Analysis of reported gamma results for exposure 5, 15-cm D_2O-moderated ^{252}Cf, $H_g = 52(10^{-5})Sv$

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	44	0.62 - 15.81	1.80 ± 3.10
Subset[b]	41	0.62 - 1.63	1.00 ± 0.23
TLD-100	3	1.44 - 14.49	5.81 ± 6.14
TLD-700	14	0.62 - 7.88	1.40 ± 1.81
TLD-BeO	1	0.79 - 0.79	0.79 ± 0.00
TLD-$CaSO_4$	3	1.05 - 15.81	5.99 ± 6.94
TLD-$Li_2B_4O_7$	17	0.71 - 1.24	0.92 ± 0.13
Film	6	1.15 - 1.41	1.27 ± 0.11

[a]Reported gamma dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 26. Analysis of reported gamma results for exposure 6, $^{238}PuBe$, $H_g = 1(10^{-5})Sv$

Dosimeter type	Number of participants reporting	Normalized results[a]	
		Range	Mean ± σ
All	34	0.00 - 21.33	3.38 ± 5.12
Subset[b]	24	0.00 - 2.67	1.00 ± 0.98
TLD-100	3	0.00 - 20.00	6.67 ± 9.43
TLD-700	11	0.00 - 10.00	2.37 ± 2.73
TLD-BeO	0	0.00 - 0.00	0.00 ± 0.00
TLD-$CaSO_4$	2	0.00 - 0.00	0.00 ± 0.00
TLD-$Li_2B_4O_7$	16	0.00 - 21.33	3.04 ± 4.92
Film	2	10.00 - 10.00	10.00 ± 0.00

[a]Reported gamma dose equivalents divided by reference value.
[b]Subset refers to reported data less than three times the reference value.

Table 27. Analysis of total dose equivalent for PDIS 14 exposures

Exposure number	No. participants reporting[a]		Normalized subset results[c]	
	All	Subset[b]	Range	Mean ± σ
1	36	34	0.69 - 2.75	1.29 ± 0.47
2	39	39	0.72 - 2.94	1.17 ± 0.45
3	39	39	0.39 - 2.99	0.97 ± 0.49
4	39	36	0.33 - 2.68	1.39 ± 0.52
5	40	35	0.48 - 2.47	1.19 ± 0.40
6	32	29	0.00 - 2.44	0.99 ± 0.65

[a]Not all participants reported both neutron and gamma (i.e., total) dose equivalent.
[b]Subset refers to reported data less than 3 times the reference value.
[c]Reported total dose equivalent divided by reference value.

END

DATE FILMED

02 / 13 / 91