Response Characteristics of Selected Personnel Neutron Dosimeters

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**Pacific Northwest Laboratory
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RESPONSE CHARACTERISTICS OF SELECTED
PERSONNEL NEUTRON DOSIMETERS

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FOREWORD

Response characteristics of selected personnel neutron dosimeters in current use at Department of Energy (DOE) facilities were determined as part of the DOE Personnel Neutron Dosimeter Upgrade Program. This determination is important to achieving the overall objectives of the program for several reasons, including:

- providing a uniform assessment of performance characteristics for personnel neutron dosimeters in routine use by several DOE laboratories
- measuring the accuracy and reproducibility of personnel neutron dosimeter dose evaluations in known radiation fields
- establishing a basis for comparison of prototype personnel neutron dosimeters currently under development
- comparing current personnel neutron dosimetry performance with existing and proposed dose limits
- identifying any current personnel neutron dosimeter concepts which are superior in performance.

It is important to point out at the outset that the data contained herein may not be totally indicative of the accuracy of occupational doses determined routinely by the respective laboratories. Several laboratories utilize supporting field instrument data, such as measurements using rem meters, tissue equivalent proportional counters, and/or 3-inch and 9-inch sphere measurements, in evaluating the occupational dose received. In addition, all results herein are strictly blind in that no laboratory's data are explicitly identified.

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EXECUTIVE SUMMARY

A series of personnel dosimeter neutron irradiations was carried out to determine certain performance characteristics of selected personnel neutron dosimeters that are in current use at Department of Energy (DOE) facilities. These irradiations were quite specialized since they employed only well defined beams and a few highly standardized neutron sources. Information obtained was not intended to directly evaluate any participating laboratory's ability to determine occupational dose. Many laboratories utilize additional information such as field measurements of neutron dose and spectra to arrive at actual personnel doses. Since the neutron sources were so highly standardized, they could be used to determine the inherent accuracy and precision, along with the lower detection limit and energy dependence of each type of dosimeter.

This program was designed to provide a consistent evaluation of certain common characteristics of the different dosimeters in use by exposing all the types employed in this study to the same radiation fields. The processing and read-out of the dosimeters was carried out by the participating laboratories.

The results of this study form a useful data base which should provide valuable information to the participants. They may determine their performance relative to the range of other participants from the information in this report. This information is available to the participants, although the results are presented in this report in a strictly blind manner. In addition, since there were some neutron fields used in this study which may not have been previously encountered by the participants, they may determine their energy dependent corrections for these fields relative to the calibration neutron field of unmoderated ^{252}Cf .

The findings of this study are described in detail in the text and in Appendix A. Only the highlights are given here. First, as to the accuracy as determined by these tests, it was found that when all of the laboratories employed a common set of calibrations, the overall accuracy was approximately $\pm 20\%$, which is within uncertainty expected for these dosimeters. For doses

above 80 mrem, the accuracy improved to better than 10% when a common calibration was used. Individual differences found in this study may reflect differences in calibration technique rather than differences in the dose rates of actual calibration standards. Second, at dose rates above 100 mrem, the precision for the best participants was generally below $\pm 10\%$ which is also within expected limits for these types of dosimeters. The poorest results had a standard deviation of about $\pm 25\%$. At the lowest doses, which were sometimes below the lower detection limit, the precision often approached or exceeded $\pm 100\%$. Third, the lower level of detection for free field ^{252}Cf neutrons generally ranged between 20 and 50 mrem. Fourth, the energy dependence study provided a characterization of the response of the dosimeters to neutron energies far from the calibration energy. This information confirmed the known significant neutron energy response dependence for conventional personnel dosimeters, and reaffirms the need for appropriate calibration factors to provide an accurate determination of neutron dose equivalent.

ACKNOWLEDGMENT

Several people were instrumental in the successful completion of this effort. The involvement of people at each participating laboratory is gratefully acknowledged. Their comments during the course of the program and on the draft copy of this report are very much appreciated. E. J. Vallario is the DOE Program Manager for this Personnel Neutron Evaluation and Upgrade Program, and his interest in the successful completion of this effort is gratefully appreciated. Yo T. Song and John Taylor, chairmen of the Program Review Committee and the Program Scientific Advisory Committee, respectively, were instrumental in defining the scope of the intercomparison task. Special acknowledgment is due Pat Sickie of PNL who coordinated the receipt, irradiation, and return of the many dosimeters involved in this effort.

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RESPONSE CHARACTERISTICS OF SELECTED PERSONNEL NEUTRON DOSIMETERS

INTRODUCTION

Performance characteristics of selected personnel neutron dosimeters in current use at Department of Energy (DOE) facilities were determined from their evaluation of neutron dose equivalent received after irradiations with specific neutron sources at either the National Bureau of Standards (NBS) or the Pacific Northwest Laboratory^(a) (PNL). The characteristics assessed included: lower detection level, energy response, precision and accuracy. The data collected were evaluated in three phases:

- Phase 1 - Dosimeter irradiations were carried out during February, March, and April of 1981, consistent with ANSI N13.11 (American National Standards Institute 1978) recommendations, and the dose equivalent was evaluated using participant-specific calibration data.
- Phase 2 - Re-evaluation of Phase 1 dosimeter results was performed by participants using PNL-supplied calibration data appropriate to the irradiation laboratory's neutron sources.
- Phase 3 - Subsequent irradiations during May, June, July, and August 1981 were carried out using additional neutron sources, including a moderated ^{252}Cf source, a ^{252}Cf source in a high scatter facility, and mono-energetic neutrons using the PNL Van de Graaff accelerator and NBS reactor filtered beams.

The DOE laboratories participating in the program are shown in Table 1. The procedure for carrying out the intercomparison was as follows: Each month, 35 dosimeters including 5 control dosimeters were submitted to PNL for irradiation by each participant. PNL coordinated the irradiation of dosimeters between NBS and PNL. After irradiation, the dosimeters were returned to the

(a) Operated by Battelle Memorial Institute.

TABLE 1. Participants in Program

Argonne National Laboratory (ANL)
Brookhaven National Laboratory (BNL)
Hanford
Idaho National Engineering Laboratory (INEL)
Los Alamos National Laboratory (LANL)
Lawrence Livermore National Laboratory (LLNL)
Mound Laboratory
Nevada Test Site (NTS)
Pantex
Rocky Flats Plant (RFP)
Sandia Laboratories
Savannah River Plant (SRP)

respective laboratories for evaluation. The analysis and presentation of results in this report are strictly blind, in that no identification of the laboratories is shown in the data tables.

The types of dosimeters included in this study were, for the most part, TLD-albedo designs. However, the nuclear track emulsion (NTA) film dosimeter is still in use and was included in this study due to its ability to respond to high energy neutrons. Several variations of the basic albedo principle of detecting neutrons reflected from the body as well as incident thermal neutrons using ^6LiF and ^7LiF TLDs have been developed. Figure 1 shows some typical dosimeter configurations.

Figure 2 shows the dosimeters used in this study. This figure helps to point out that the dosimeters have different geometrical configurations and probably employ different calibration, processing, and dose determining procedures.

It is difficult to define the basic mechanisms that result in a high or a low accuracy dosimeter. The overall performance of each dosimeter is a combination of the dosimeter design as well as processing, calibration and dose algorithm procedures. The physical principles upon which each dosimeter type relies for its response do not necessarily limit accuracy. The dosimeter

FIGURE 1. Schematic Representation of Some TLD-Albedo Dosimeters Used at DOE Facilities

response as a function of neutron energy is complex, and it is also dependent upon the physical principles of operation and upon the details of construction and calibration.

Neutrons produce most of their effects in solids by means of secondary charged particles resulting from elastic and inelastic scattering, nuclear interactions, and the eventual generation of protons, alpha particles, electrons and possibly heavy charged particles. The energy spectra and angular distributions of these charged particles are intricate, and in some cases, poorly known. Therefore, it is difficult to accurately characterize the response to neutrons for even the simplest dosimeter. For example, consider the case of dosimeters based on the use of nuclear emulsions, which rely on the registration of charged particle tracks that are visible after development, and can be counted using optical means. A plot of the response function for a typical nuclear emulsion is shown in Figure 3. The yield of tracks per neutron as a function of neutron energy for Kodak Type A film rises from about 500 keV to a maximum at about 7 MeV and then begins to fall (Dudley 1966). This response may be due to a situation where more than the energy necessary

FIGURE 2. Participant Dosimeters Used in Irradiation

FIGURE 3. NTA Response as a Function of Neutron Energy (Dudley 1966)

to produce an effect is deposited locally by the densely ionizing secondary charged particles from higher energy neutrons. Since the statistical uncertainty is large for low neutron doses and the response to low energy neutrons rapidly decreases for nuclear emulsions, it can be expected that their performance under such conditions will be poor.

TLD sensitivity to low and intermediate energy neutrons is generally quite good due to its inherently larger quantum efficiency. A single charged particle can excite an electron to the conduction band from which it can migrate to a trap and, on subsequent heating, recombine with a free hole to produce a visible light photon. On the other hand, a charged particle track may not be produced in an emulsion unless the particle has sufficient energy. Low doses result in very few individual tracks which are difficult to detect.

The energy response of TLD albedo dosimeters is also complex due to the response of the phosphors themselves and the details of the irradiation geometry (Brackenbush 1980). In general, they are very sensitive to low and intermediate energy neutrons. The response as a function of neutron energy for three types of TLD is shown in Figure 4 (Piesch 1978). The response for

FIGURE 4. Energy Dependence of Various Albedo Dosimeters (Piesch and Burgkhardt 1978)

of all the TLDs, begin to decrease above 10 keV and continues to decrease exponentially for higher neutron energies. From this figure, it is clear as to why it is difficult to obtain accurate dose results for the variety of neutron spectra encountered in the work environment.

Both TLD and NTA films are subject to several sources of uncertainty in the repeated determination of dosimeter response to the same given dose. TLD phosphors may not be completely uniform and it is generally not practical to establish a calibration factor for each individual dosimeter. Counting tracks in NTA films is a statistically variable process. It is necessary to count a relatively large number of tracks for good statistics, however, counting large numbers may again be impractical. Therefore, a compromise must be achieved which will affect precision.

Each of these dosimeters is inherently quite sensitive in terms of absorbed dose within certain energy ranges, but there are limits to the signal-to-noise ratio for each one. Basically, the limiting processes are at work in the read-out systems. TLD systems are limited by photomultiplier dark current and

sample holder heating incandescence. NTA films are affected by environmental factors such as heat, light, and moisture.

The response of a personnel dosimeter to neutrons can be represented by the integral of the dosimeter response function $R(E)$ over the neutron energy spectrum $N(E)$ dE ,

$$D = \int_{E_{\min}}^{E_{\max}} R(E) N(E) dE$$

where D represents the total dosimeter response. In practice, the dosimeter response is determined with a calibration source and this response is used to evaluate the dose received during field use. It is important to note that since the response functions are strongly energy dependent, the calibration source spectrum is critical. For instance, it is easy to see that if one uses a calibration source with an energy spectrum primarily above 1 MeV and a measurement is taken in a low energy field, then the dose may be overestimated by some orders of magnitude (see Figures 3 and 6).

NEUTRON SPECTRA

Neutron energies encountered in the laboratory and in the field extend over many orders of magnitude. Neutron spectral measurements with a multi-sphere system are shown in Figure 5 for a plutonium fuel fabrication facility (Aldrich 1981). The average energies as calculated are:

- 530 keV in the fuel storage pit area
- 576 keV in the plutonium storage vault
- 660 keV in the fuel pin storage box area
- 1.1 MeV in the pin storage area
- 1.5 MeV at the midpoint of the bare fuel subassembly.

The unmoderated and slightly moderated neutron fields result in high energy spectra. In the storage pit and vault there is a higher contribution of thermal and intermediate neutrons because of neutron scattering in the additional shielding and from the building.

FIGURE 5. Neutron Spectra Measured by a Multisphere Spectrometer at a Plutonium Fuel Fabrication Facility (Aldrich et al. PNL-3536, Study 4, 1981)

DOSIMETER IRRADIATIONS

Sources of neutron radiation used in this program are listed in Table 2 from NBS and PNL. Several measurements were made to characterize the neutron spectra and dose equivalent from these sources using two and five-inch tissue equivalent Bonner spheres and laboratory evaluated personnel dosimeters.

TABLE 2. Neutron Sources

NBS

- . unmoderated ^{252}Cf
- . moderated ^{252}Cf .
- . monoenergetic neutrons of 2, 24, and 144 keV

PNL

- . unmoderated ^{252}Cf
- . high scatter geometry ^{252}Cf
- . monoenergetic neutrons between 100 keV and 4 MeV using the PNL Van de Graaff accelerator and selected targets

NATIONAL BUREAU OF STANDARDS

Neutron irradiations at NBS were carried out using a moderated and an unmoderated ^{252}Cf source, a 15 cm D_2O moderated ^{252}Cf source, or one of the beams from a 10 megawatt reactor. Figures 6 and 7 show the spectra from unmoderated and moderated ^{252}Cf source as calculated by Schwartz (1980) and Grundl (1975).

Californium-252

Unmoderated

The NBS ^{252}Cf source is a lightly encapsulated source which is pulled up by a string into an aluminum jig which fixed its position during irradiation. The source is housed in a low scatter area of an accelerator target pit with a

FIGURE 6. Bare ^{252}Cf Neutron Spectrum

FIGURE 7. Moderated Fission Source Spectrum

grid floor. Lightweight aluminum scaffolding provides a mounting platform for the phantom and dosimeters. The room is approximately 11 m x 11 m x 11 m and the source is stored in a well within the floor.

Moderated Californium-252

A moderated ^{252}Cf spectrum is achieved by using an assembly with a cadmium-covered 15-cm radius sphere of D_2O with a ^{252}Cf source at the center. Several measurements were made to determine the uncertainty in the calculated dose equivalent rate. The overall uncertainty compared to the unmoderated californium source is estimated to be $\pm 3\%$ exclusive of any uncertainties in fluence to dose equivalent conversion factors. The uncertainty in the dose equivalent rate from the moderated source is, however, estimated to be $\pm 15\%$. This is almost entirely due to uncertainties in the details of the spectrum shape (Schwartz 1982).

Filtered Reactor Beams

Three nearly monoenergetic beams in addition to a thermal beam are available from the 10 megawatt NBS reactor. These beams are available using selected filters having sufficiently small cross-sections over small energy bands to allow transmission of neutrons of nearly the same energy (Schwartz 1977). These are described as follows:

1. 2 keV. Scandium filtered beam with 97% of the flux density in the 2 keV region.
2. 24.3 keV. Iron-aluminum filtered beam with 97% of the flux density within the main peak. The other 3% is in higher energies.
3. 144 keV. Silicon filtered beam with two peaks: 98% and 1.5% of flux density are within 144 keV and 51 keV peaks, respectively.

The measured spectra for the filtered beams are shown in Figures 8 through 10. The filtered beams are very small being about 1-inch in diameter and well collimated. The beams travel through a port about 1 meter in length. At a distance of 2 meters, the beams are only about 2-inches (5 cm) diameter. For these irradiations, dosimeters are mounted on a 30-cm by 30-cm phantom, 15-cm in thickness. A 25-cm by 25-cm scan of the dosimeters is done using beams of

FIGURE 8. Nominal 2 keV Filtered Reactor Beam

FIGURE 9. Nominal 24 keV Filtered Reactor Beam

FIGURE 10. Nominal 144 keV Filtered Reactor Beam

5 cm in diameter and a flux density of 5×10^4 n/cm²-sec. The dosimeters on their phantom are scanned to achieve uniform irradiation, using an x-y motor drive.

PACIFIC NORTHWEST LABORATORY

Dosimeters were irradiated using an unmoderated ²⁵²Cf source in the 318 facility, an unmoderated ²⁵²Cf source in a high scatter geometry in the 3645A facility, and monoenergetic neutron beams using the PNL Van de Graaff accelerator.

A relatively large room is desirable for neutron irradiations because of the large amount of secondary scattering from room surfaces (Schwartz and Eisenhauer 1982). The room dimensions in the 318 facility are shown in Figure 11. The minimum distance to a room surface is 4.1 m for the ²⁵²Cf source. All room surfaces are made of concrete.

The ²⁵²Cf source is pulled into position using a cord-and-pulley system. The source moves inside stainless-steel tubing. It is stored inside a

FIGURE 11. Schematic Diagram of Low-Scatter Irradiation Room

paraffin-filled drum. The irradiation geometry for the ^{252}Cf source is shown in Figure 12. The source is pulled into the irradiation position, at a height corresponding to the center of the phantom. The dosimeters are irradiated on the front face of a 30 cm x 30 cm x 15 cm water-filled phantom. The distance between the source center and the front face of the phantom is 50 cm. The ^{252}Cf source (approximately 9 μg) in the form of a cylinder 23.1 mm long by 2.8 mm in diameter, encapsulated by 0.88 mm of iridium and platinum.

Aluminum scaffolding is used to provide platforms for mounting dosimeters and equipment. The scaffolding does not contribute a measurable amount of scattered radiation to the ^{252}Cf exposures.

Van de Graaff Accelerator

The neutron irradiation facility at the PNL Van de Graaff accelerator laboratory has a neutron producing target located over the center of a 6 m x 6 m pit and grid flooring, with the target 3 m from the pit floor.

Irradiations using a tritium target were done at 45° with respect to the primary beam and at a target to front face of phantom distance of 75 cm. The precision long counter was at a complementary angle, at an effective target to detector distance of 100 cm. Exposures using the deuterium target were done with the phantom at 0° and a distance of 75 cm, and the precision long counter positioned at 45° . Precision long counter data at 0° and 45° were used to establish the fluence at the phantom surface.

FIGURE 12. ^{252}Cf Irradiation Geometry

The phantoms were 30 cm x 30 cm x 16 cm lucite tanks with 0.64 cm thick walls, which were filled with water. The dosimeters were taped as close as possible to the center of the face of the phantom, and up to 6 dosimeters were irradiated at one time.

PNL ^{252}Cf CALIBRATION TRACEABILITY

Traceability of the ^{252}Cf source is based on an NBS emission rate calibration. A conversion factor of 3.4×10^{-8} rem-cm² (ANSI 1978) was used to convert to absorbed dose equivalent rate at the calibration point. The most recent accepted value is 3.33×10^{-8} rem-cm⁻² (Schwartz 1982). The ^{252}Cf source strength is corrected for decay according to a 2.65-year half life.

Correction to the dosimeter readings for neutrons scattered in the exposure facility were calculated using tabulated values developed by NBS (Schwartz 1982). The correction factors, expressed as a percent of the signal due to the unscattered or free-field neutrons for albedo dosimeters, at 50 cm,

were 0.8% (air scatter), 1.3% (source scatter), and 4.5% (room return), for a total of 6.5%. The correction factors for dose equivalent totalled 1.3%.

The room return correction for the albedo dosimeter was checked using laboratory evaluated thermoluminescent dosimeters. Groups of six dosimeters were irradiated at distances of 35 cm, 70 cm, 100 cm, 140 cm, and 200 cm from the source. Each dosimeter contained ten tightly screened TLDs which were read manually. After background subtraction, dosimeter responses were corrected for sources and air scatter and normalized to a free field dose of 1000 mrem based on irradiation time.

We assumed that the fluence of room scattered neutrons was uniform over the central portion of the room (Schwartz 1982). Therefore, a plot of $D(r)r^2$ versus r^2 would be linear, where $D(r)$ is the dosimeter response at distance r . A linear least squares fit to the data points was used to obtain a slope and intercept. The scatter correction in percent per square meter was obtained by dividing the slope by the intercept. The plot is shown in Figure 13. The measured room return correction is $12\%/m^2$. Using this value the total scatter correction is 5.9%, compared to the calculated results of 6.5%.

The gamma component from the ^{252}Cf source was estimated from the TLD-700 response relative to a ^{137}Cs calibration. At 50 cm, the penetrating gamma component was approximately 5% of the free-field neutron dose-equivalent rate.

^{252}Cf SOURCE DOSE CALCULATION

Using the neutron emission rate determined at NBS, the free-field given dose is calculated by:

$$H = \frac{N \cdot C_N \cdot t \cdot 3600}{4 \pi \cdot r^2}$$

where N = the neutron emission rate at the time of irradiation (n/sec).
The source is decay corrected with a half life of 2.65 yr

C_N = the dose-equivalent conversion factor ($\text{mrem}/\text{cm}^2/\text{h}$). The 1978 draft of ANSI N13.11 specifies $3.4 \times 10^{-5} \text{ mrem}/\text{cm}^2/\text{h}$. The present value is $3.33 \times 10^{-5} \text{ mrem}/\text{m}^2/\text{h}$ (Schwartz 1982)

FIGURE 13. Room Return PNL Laboratory Dosimeter Using 1.1% m Air Scatter

t = the irradiation time (h).

r = the distance from the source center to the calibration point (cm).

Dosimeter and TEPC measurements for the high scatter geometry in the 3745A building were initially performed at three distances from the source in several directions. Data for each distance were averaged. The measured room return was $19\%/m^2$ for the dosimeter and $18\%/m^2$ for the TEPC. Measurements were repeated with laboratory evaluated dosimeters placed along a single direction from the source. Linear regression for these seven distances showed significant scatter, and that the data are not homogeneous by direction. Thus, the averaging process may not be valid.

Room scatter determinations were also performed by PNL personnel at NBS for the unmoderated ^{252}Cf sources. A room return of $19\%/m^2$ was found for dosimeter measurements with the unmoderated source, the room return for the moderated source is significantly lower, approximately $6\%/m^2$. The TEPC response to scatter was a function of detector size, with the 5" TEPC yielding scatter factors of $7\%/m^2$ and $5\%/m^2$ respectively for the unmoderated and moderated sources. The 2-in. TEPC scatter factors were $5\%/m^2$ for both NBS sources.

Using the dosimeter measurements of room return, the tabulated air scatter values and the calculated source scatter terms, the total scatter correction at 50 cm was 6% for the PNL source in the 318 facility, 8% for the NBS unmoderated source, and 5% for the NBS moderated sources. Dosimeter results were reduced by the appropriate scatter corrections to provide estimates of the "free field" response.

DATA ANALYSIS

The analysis of personnel neutron dosimeter response is divided into four areas: 1) the accuracy and precision of dosimeters currently in use at DOE facilities when exposed to unknown doses of unmoderated ^{252}Cf ; 2) the accuracy and precision of the same dosimeters when calibration information is provided to the DOE contractors; 3) the lower detection limit of neutron dosimeters in current use; and 4) the energy dependence of dosimeters calibrated solely to unmoderated ^{252}Cf . Results are reported in a strictly blind manner without identifying the participating laboratories. All data, including outliers, were used unless specifically flagged as bad by the contractor or by the irradiation facility. A compilation of data is contained in Appendix A.

ACCURACY AND PRECISION

The accuracy of dosimeter response is a measure of how close the reported dose is to the dose given. This will be defined as:

$$b_i = \frac{R_i - G_i}{G_i} \quad (1)$$

where b_i is the accuracy or relative bias of the individual dosimeter response, R_i is the reported dose, and G_i is the given dose. The use of the relative bias as an estimator of accuracy is used instead of the bias alone so that irradiations at various dose levels can be readily compared.

All irradiations were performed in replicate according to the schedule of Table 3. To evaluate the accuracy of n dosimeters irradiated at the same dose we use:

$$B = \frac{1}{n} \sum_{i=1}^n b_i \quad (2)$$

where B is the mean relative bias or accuracy at a given dose level and b_i is defined in equation (1). Since we are dealing with the relative bias, equation (2) can also be used to estimate accuracy over all dose levels.

TABLE 3. Number of Neutron Dosimeter Irradiations by Month,
Radiation Type and Exposure Level

Radiation Type		Dose in mrem	Feb	Mar	Apr	May	Jun	Jul	Aug
1. Unmoderated ^{252}Cf	10	7	7	6					
	20	8	8	4					
	80	5		10					
	250				5				
	300	5	10	5		5			
	800	5	5	5					
	Random	5	5	5					
2. Unmoderated ^{252}Cf (high scatter)	0				5				
	50				10				
	90				10				
	250				5				
3. Moderated ^{252}Cf	5					5			
	10					5	5		
	20					5	5		
	80						5		
4. Accelerator 0.5 Mev	50							5	
	100							5	
	1.9 Mev	50					5		
	100						5		
	5.0 MeV	50							5
	100								5
	200							5	
5. Reactor	25 keV	50							5
	100								5
	2 keV	25							5
	Thermal	25							5
6. Controls			5	5	5	5	5	5	5
Total			40	40	40	40	35	35	35

Precision of dosimeter response or repeatability is measured by the coefficient of variation, CV. This statistical estimator is defined as:

$$CV = S/\bar{R} \quad (3)$$

where S is the standard deviation of each group of dosimeters and $\bar{R}$ is the mean reported dose. It expresses variation in reproducibility relative to the magnitude of the dose reported and is independent of the bias. This statistical estimator permits comparisons of precision between contractors even though their accuracies may differ. To calculate the estimated precision at a given dose, we use:

$$P_D = CV \cdot D \quad (4)$$

where P_D is the estimated precision at a given dose, D, and CV is taken from the best estimate or closest mean to that dose.

Phase 1

Phase 1 of the personnel neutron dosimeter response study involved irradiations for the months of February, March, and April (see Table 3). The participating DOE contractors were asked to use their own calibrations. The dosimeter response measured by accuracy and precision is graphically represented in Figures 14 and 15. A large variation in accuracy is seen particularly at the lower exposure levels. The range of accuracies at 10 mrem is from -1.71 to +2.31 and is accompanied by a large coefficient of variation (52% of the dose). The higher doses, particularly the 800 mrem, show a much narrower range (-0.66 to +0.08) with most contractors underestimating the given value.

A specific problem was encountered with the data from one contractor. Contractor I reported absolute biases of 2.31 and 1.32 at 10 and 20 mrem, respectively. These are based on only March data, and appear as obvious outliers. Data for the other months was lost due to dosimeter fading as dosimeters were not given adequate dessicant.

Overall Phase 1 results indicate a 20-30% underestimate of dose by most DOE contractors. Further, the precision at low doses averages approximately 100% of the dose given, indicating difficulty in detecting 10 and 20 mrem neutron doses.

ACCURACY

FIGURE 14. Bias for Various Dose Levels for Phase 1 and Phase 2

PRECISION

FIGURE 15. Precision for Various Dose Levels for Phase 1 and Phase 2

Phase 2

The DOE contractors were provided with uniform calibration information for the second part of the dosimeter study. This information included the type of neutron source, the irradiation parameters (room size, phantom description, source location) and the identity of all control (0 mrem) and 300 mrem irradiated dosimeters for the months of February, March, and April. Also included were controls and 250 mrem irradiated dosimeters for the month of May. Using this information, all contractors were requested to recalculate the dosimeter response of Phase 1 irradiations. Three contractors failed to provide the recalculated data, contractors I, J, and K, and Phase 2 results reflect a summary of the other 9 contractors.

Figures 14 and 15 indicate the accuracy and precision of Phase 2 results. A noticeable improvement is seen in accuracy after recalibration. Again the wide spread of accuracy is seen at the lower dose levels with a very narrow range at the higher doses. The average accuracy for all contractors for all dose levels is 0.11 with most of this positive absolute bias attributed to the 10 and 20 mrem irradiations. The 80, 300, and 800 mrem doses are within 5% of the given value. Figure 16 demonstrates the dramatic effect of recalibration on accuracy. Precision remains essentially the same for Phases 1 and 2 as would be expected. There is a small improvement seen at the higher irradiation levels (see Figure 17). If we restrict ourselves to irradiations above 50 mrem, most contractors have both accuracies and precisions below 0.20.

LOWER DETECTION LIMIT

A very useful parameter in defining neutron dosimeter response is the minimum irradiation level that a set of dosimeters can reliably detect. This detection point has been called by different names but for our purposes will be called the lower detection limit (L_D). This will be defined as

$$L_D = K_\alpha \sigma_0 + K_\beta \sigma_D \quad (5)$$

where L_D is the lower detection limit of a contractor's dosimeter system, K_α and K_β are the abscissas of the standardized normal distribution corresponding to the probability levels $1-\alpha$ and $1-\beta$, respectively σ_0 is the

ACCURACY

FIGURE 16. Plot of Accuracy for Phase 1 and Phase 2 Data

PRECISION

FIGURE 17. Plot of Precision for Phase 1 and Phase 2 Data

standard deviation of controls and σ_0 is the standard deviation at the detection limit. The values for α and β are the desired probability levels for false positive and false negative results (type 1 and type 2 errors) that are acceptable. Commonly these are set equal and chosen to be 5, 10, or 20%. A further discussion of equation (5) is found in an article by Curie (1968).

To estimate the lower detection limit requires the value of σ_0 or the standard deviation. The data provided by the control dosimeters in this study were not always reliable because negative results were often reported as zeros and the relatively small number of dosimeters make estimating the standard deviation difficult. Regression analysis of the data often yielded intercepts very different from mean control values, although the linearity and correlation of fit were extremely good. Estimates of the standard deviation for control dosimeters and 10 mrem irradiated dosimeters were used to determine a suitable value for σ_0 for each of the contractors.

Figure 18 summarizes the lower detection limits for all contractors assuming acceptable errors of 5, 10 and 20%, both α and β being equal. Most contractors have a lower detection limit between 20 and 50 mrem (using a 10% acceptable error). Two contractors, C and J, are able to distinguish the 20 mrem irradiations from background. On the other extreme, contractors E and L can do no better than 130 and 210 mrem, respectively. Overall, the average lower detection limit is 50 mrem at the 10% acceptable error level.

Phase 3 - Energy Dependence

During the months of May, June, July, and August the neutron dosimeter study focused on the energy dependence of dosimeter response. During May, dosimeters were irradiated to unmoderated ^{252}Cf in a smaller irradiation facility where the scatter was increased. Control or 0 mrem irradiated dosimeters were included for both the high scatter environment and the normal low scatter storage area. Also dosimeters irradiated to 250 mrem in the PNL low scatter facility were provided for comparison. Figure 19 summarizes this data and indicates an average over-response of approximately 35% in the high scatter environment. This agrees with long counter and tissue equivalent proportional counter measurements made in the high-scatter facility, indicating the effect of room size on dosimeter response.

MINIMUM DETECTION LIMIT

FIGURE 18. Histogram of Estimated Lower Detection Limits for All Contractors at 3 Levels of Acceptable Error, 5%, 10% and 20% ($\alpha = \beta$)

**PHASE 3 ACCURACY
HIGH SCATTER VS LOW SCATTER Cf-252**

FIGURE 19. Histogram of Neutron Dosimeter Response in a High Scatter Environment (HS) Compared to a Low Scatter Environment (LS)

Dosimeters were irradiated by moderated ^{252}Cf at NBS during June and July. Figure 20 shows the large over-response of dosimeters, which were calibrated to the higher energy bare ^{252}Cf , at irradiation levels of 5, 10, 20, and 80 mrem. This over-response is consistent at about 1120% of the dose.

Accelerator irradiations at energies of 0.5, 1.9, and 5.0 MeV were also done during Phase 3. Results are summarized in Figure 21. Here we see a 100% over-response at the low energy, a slight over-response at 1.9 MeV (an energy similar to the unmoderated ^{252}Cf used for calibration) and a 64% under-response at the high energy.

Reactor irradiations at very low energies of 25 keV, 2 keV and thermal neutrons show very large over-responses (see Figure 22). The 25 keV response averages 3800% of the dose, the 2 keV is 10,900% and the thermal is 11,600%. Clearly when evaluating neutron dosimeter response it is necessary to know the energy spectrum or field to which the dosimeters are exposed, and to calibrate them appropriately.

**PHASE 3 ACCURACY
MODERATED Cf-252**

FIGURE 20. Histograms of the Accuracy of Neutron Dosimeter Response During Phase 3 Irradiations to Moderated ^{252}Cf by Irradiation Level

PHASE 3 ACCURACY
ACCELERATOR-PRODUCED NEUTRONS

FIGURE 21. Histograms of the Accuracy of Neutron Dosimeter Response to the Three Energies of Monoenergetic Neutrons

PHASE 3 ACCURACY
FILTERED REACTOR BEAMS

FIGURE 22. Histograms of the Accuracy of Neutron Dosimeter Response to Various Energies of Reactor Beams

DISCUSSION

Some of the characteristics which may have influenced dosimeter performance include: design and construction; calibration and dose determination procedures; and processing and handling techniques. It is difficult to identify which of these items affected performance in terms of accuracy, precision, lower-limit detection or energy response. This study was not specifically designed to answer these questions. In order to do so, a much more specific set of tests would have to be designed to isolate the influence of each potential source of uncertainty. This could, however, be the subject of future investigations.

In general, there was little observable difference between the design and construction details of good and poor performance dosimeters. Nearly all of the designs tested were TLD-albedo dosimeters with either complete cadmium shielding (Hankins-type) or front and back (asymmetric) cadmium shielding. No systematic difference in performance could be found between these designs.

The dose determination procedures and processing methods were all quite similar, although some small differences in dose algorithms were reported. This situation seems, therefore, unlikely to be a major contributing factor to large differences in performance.

Some of the laboratories having good accuracy and precision during this study reported the use of a single set of dosimeters throughout. This procedure would probably enable closer tracking of individual dosimeter response characteristics and thereby enhance precision and possibly accuracy. However, this handling procedure may not be practical in the situation where large numbers of dosimeters are processed.

The calibration situations at each participating laboratory were sufficiently different to warrant consideration as a potential source of uncertainty, but there is insufficient data in this report to reach a firm conclusion. It can only be noted that when all participants used a common calibration during Phase 2 of this project, then the overall accuracy was generally improved. The details of calibration methods and sources would be a useful area for future study.

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APPENDIX A
PARTICIPANT DATA

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TABLE A.1. Means and Standard Deviations (SD) of Phase 1 Neutron Dosimeter Response Reported by Contractor and Irradiation Level. All results are reported in mrem. Total Mean and SD includes all dosimeters irradiated during Phase 1. Response for contractor I is based on March data only, the other month's dosimeters faded due to lack of constant desicant.

Contractor		CONTROL	10 MR	20 MR	80 MR	300 MR	800 MR
-----		-----	-----	-----	-----	-----	-----
A	MEAN	0.0	17.3	27.3	102.0	314.4	867.2
	SD	--	14.0	20.6	22.0	39.5	75.2
B	MEAN	-0.4	2.9	6.8	67.7	273.3	730.4
	SD	1.1	9.7	8.2	16.6	28.1	52.7
C	MEAN	-0.1	11.4	23.4	88.9	305.5	814.7
	SD	1.3	5.5	13.7	10.6	44.7	36.4
D	MEAN	0.0	13.6	21.7	60.0	155.0	435.5
	SD	--	12.9	16.2	16.1	22.0	59.1
E	MEAN	3.0	12.7	18.5	56.8	122.5	424.3
	SD	12.4	22.8	24.6	30.7	49.9	166.2
F	MEAN	1.3	4.2	7.3	30.2	105.1	282.5
	SD	2.2	4.6	3.4	6.4	28.6	85.7
G	MEAN	4.0	10.0	15.8	44.7	156.7	403.9
	SD	2.4	3.2	4.9	7.8	26.1	79.5
H	MEAN	1.5	14.8	28.6	74.4	257.5	692.7
	SD	8.3	11.4	13.8	19.1	54.1	145.1
I	MEAN	12.8	33.1	46.4	--	401.0	774.4
	SD	7.1	17.0	15.2	--	53.0	55.0
J	MEAN	0.4	3.3	8.0	26.6	96.1	271.3
	SD	1.7	2.9	2.9	6.7	13.3	26.2
K	MEAN	0.6	16.8	27.7	82.6	293.4	768.7
	SD	8.5	3.1	5.7	9.6	34.6	78.2
L	MEAN	-0.2	-7.1	15.7	27.8	250.2	722.2
	SD	29.2	25.7	32.4	35.2	86.5	125.6
TOTAL	MEAN	1.3	10.1	19.6	62.4	222.8	603.9
	SD	10.2	15.4	18.4	30.6	97.4	225.0

TABLE A.2. Mean and Standard Deviation Summary of February Data, Phase 1. Contractor J did not participate this month and I experienced dosimeter fading. Total Mean is the average neutron dosimeter response for all contractors.

Contractor		CONTROL	10 MR	20 MR	80 MR	300 MR	800 MR
A	MEAN	0.0	15.7	30.4	87.0	312.9	830.2
	SD	--	18.5	24.6	10.0	24.2	46.8
B	MEAN	0.0	0.0	6.5	53.6	284.6	728.2
	SD	--	--	9.2	4.8	33.2	41.7
C	MEAN	0.1	9.4	18.8	88.9	333.2	825.2
	SD	2.4	4.0	4.2	12.9	14.5	42.6
D	MEAN	0.0	11.5	18.1	59.0	167.5	477.8
	SD	--	7.9	7.3	15.2	18.8	51.9
E	MEAN	0.7	-0.3	10.3	52.9	120.3	510.4
	SD	7.6	8.8	15.6	48.2	43.3	196.3
F	MEAN	2.6	3.8	8.1	34.8	142.1	245.1
	SD	3.1	3.6	3.8	6.1	34.6	155.3
G	MEAN	2.8	9.9	15.0	52.9	165.8	415.5
	SD	1.5	4.0	3.5	5.9	10.4	107.6
H	MEAN	6.1	24.0	34.4	94.6	308.5	805.8
	SD	8.7	8.4	12.3	14.6	33.9	61.8
I	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
J	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
K	MEAN	4.1	15.3	24.4	88.7	294.3	787.6
	SD	5.1	2.6	3.0	4.6	20.2	28.0
L	MEAN	0.2	-10.1	2.2	16.3	210.1	635.6
	SD	28.2	29.4	18.2	38.0	17.2	58.9
TOTAL	MEAN	1.8	7.9	16.8	62.9	233.9	626.1

TABLE A.3. Mean and Standard Deviation Summary of March Data, Phase 1.
No 80 mrem irradiations were measured this month.

Contractor		CONTROL	10 MR	20 MR	80 MR	300 MR	800 MR
A	MEAN	0.0	12.4	16.0	--	317.0	929.5
	SD	--	6.8	13.4	--	53.7	65.4
B	MEAN	-1.2	0.0	10.7	--	274.6	735.1
	SD	1.8	0.0	7.2	--	29.0	65.5
C	MEAN	-0.4	7.9	24.0	--	285.6	789.4
	SD	1.5	3.4	20.5	--	51.6	32.2
D	MEAN	0.0	4.6	15.2	--	143.3	406.8
	SD	--	4.7	12.6	--	16.8	26.4
E	MEAN	-4.7	0.1	10.9	--	111.6	291.0
	SD	4.1	12.9	18.3	--	41.0	70.8
F	MEAN	1.1	5.2	6.1	--	90.4	292.4
	SD	1.3	6.7	3.0	--	12.2	47.3
G	MEAN	6.5	9.8	18.4	--	165.6	447.7
	SD	1.3	3.5	5.6	--	28.4	57.8
H	MEAN	-4.1	14.0	30.7	--	257.6	767.5
	SD	4.9	6.7	12.5	--	50.7	81.1
I	MEAN	12.8	33.1	46.4	--	401.0	774.4
	SD	7.1	17.0	15.2	--	53.0	55.0
J	MEAN	0.8	4.0	7.2	--	96.3	262.9
	SD	2.0	3.5	1.8	--	12.2	23.2
K	MEAN	-11.4	17.1	29.6	--	313.4	802.1
	SD	6.0	3.5	6.6	--	28.5	87.0
L	MEAN	-0.8	-5.1	37.0	--	283.2	878.0
	SD	45.4	30.7	28.1	--	113.3	33.1
TOTAL	MEAN	-0.1	8.6	21.0	--	228.3	614.7

TABLE A.4. Mean and Standard Deviation Summary of April Data, Phase 1.
Contractor I again experienced dosimeter fading.

Contractor		CONTROL	10 MR	20 MR	80 MR	300 MR	800 MR
-----		-----	-----	-----	-----	-----	-----
A	MEAN	0.0	24.7	44.2	109.4	310.4	841.9
	SD	--	13.5	12.9	22.9	17.1	77.4
B	MEAN	0.0	9.3	0.0	75.5	259.5	727.9
	SD	--	16.3	--	15.5	18.9	60.4
C	MEAN	0.2	17.9	31.6	88.9	317.4	829.5
	SD	0.4	2.5	4.6	10.0	34.5	24.1
D	MEAN	0.0	29.1	42.0	60.5	166.0	430.4
	SD	--	12.9	21.8	17.3	24.9	76.1
E	MEAN	13.2	42.5	50.3	58.3	146.5	471.6
	SD	15.9	13.0	28.6	24.0	71.7	137.4
F	MEAN	0.0	3.6	8.2	27.9	97.6	304.6
	SD	--	2.2	3.4	5.4	6.0	11.8
G	MEAN	2.6	10.2	12.4	41.4	130.0	357.2
	SD	2.1	1.9	3.7	5.9	11.0	40.3
H	MEAN	2.5	4.9	12.7	64.4	206.4	519.7
	SD	8.6	10.9	6.5	11.7	20.7	27.0
I	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
J	MEAN	0.1	2.4	9.6	26.6	95.6	279.7
	SD	1.5	1.7	4.3	6.7	16.8	28.8
K	MEAN	3.4	18.0	30.4	79.6	252.6	716.4
	SD	7.0	2.8	6.1	10.2	18.7	88.3
L	MEAN	0.0	-6.0	0.2	33.5	224.2	653.2
	SD	11.4	18.1	44.9	34.3	28.3	70.2
TOTAL	MEAN	2.0	14.2	22.0	60.5	200.6	557.5

TABLE A.5. Accuracy of Phase 1 Neutron Dosimeter Response as Measured by the Relative Bias. Accuracy is reported by contractor and irradiation level with averages computed for each contractor. Random is a set of 15 dosimeters exposed to randomly selected doses of unmoderated Californium between 50 and 800 rem. The average total accuracy for all contractors is an underresponse of 17%. The range of neutron dosimeter accuracies by contractor is from -66% to +83%.

Contractor	10 MR	20 MR	80 MR	300 MR	800 MR	RANDOM	AVERAGE
A	.73	.36	.28	.05	.08	-.06	.26
B	-.71	-.66	-.15	-.09	-.09	-.20	-.34
C	.14	.17	.11	.02	.02	-.04	.05
D	.36	.08	-.25	-.48	-.46	-.47	-.18
E	.27	-.08	-.29	-.59	-.47	-.60	-.27
F	-.58	-.64	-.62	-.65	-.65	-.68	-.63
G	.00	-.21	-.44	-.48	-.50	-.55	-.34
H	.48	.43	-.07	-.14	-.13	-.26	.08
I	2.31	1.32	--	.34	.03	-.26	.93
J	-.67	-.60	-.67	-.68	-.66	-.66	-.66
K	.68	.38	.03	.02	-.04	--	.24
L	-1.71	-.22	-.65	-.17	-.10	-.27	-.54
TOTAL	.01	-.02	-.22	-.26	-.24	-.36	-.17

TABLE A.6. Precision of Phase 1 Neutron Dosimeter Response as Measured by the Coefficient of Variation. Precision is reported by irradiation level and contractor and averages given for each contractor across all irradiations. Note the large precision values at the lower irradiation levels indicating the difficulty in assessing response. The total average precision for all Phase 1 dosimeters is 0.79 or the standard deviation averages 70% of the reported response.

<u>Contractor</u>	<u>10 MR</u>	<u>20 MR</u>	<u>80 MR</u>	<u>300 MR</u>	<u>800 MR</u>	<u>AVERAGE</u>
A	.81	.76	.22	.12	.09	.43
B	3.34	1.20	.24	.10	.07	1.08
C	.48	.58	.12	.15	.04	.30
D	.95	.75	.27	.14	.14	.48
E	1.80	1.34	.54	.41	.39	.94
F	1.10	.47	.21	.27	.31	.50
G	.32	.31	.18	.17	.20	.24
H	.77	.48	.26	.21	.21	.40
I	.51	.32	--	.13	.07	.26
J	.87	.37	.25	.14	.10	.36
K	.18	.21	.12	.11	.10	.15
L	3.62	2.08	1.25	.35	.18	1.58
TOTAL	1.52	.94	.49	.44	.37	.79

TABLE A.7. Means and Standard Deviations (SD) of Phase 2 Neutron Dosimeter Response Reported by Contractor and Irradiation Level. Each contractor was provided calibrations information and asked to reanalyze their Phase 1 data. Contractors I, J, and K did not provide reanalyzed data. Note the significant improvement in the higher irradiation levels.

Contractor		CONTROL	10 MR	20 MR	80 MR	300 MR	800 MR
-----		-----	-----	-----	-----	-----	-----
A	MEAN	0.0	17.4	27.5	97.3	322.4	868.6
	SD	--	13.9	20.5	19.7	39.6	93.7
B	MEAN	-0.4	3.2	7.8	75.6	307.5	814.4
	SD	1.1	10.6	9.2	18.4	27.3	63.3
C	MEAN	0.2	12.9	24.2	85.9	310.2	821.5
	SD	2.0	5.6	11.0	7.2	32.2	63.5
D	MEAN	0.0	26.9	43.3	115.7	284.2	860.2
	SD	--	24.7	31.1	31.2	75.0	118.5
E	MEAN	2.4	21.1	36.8	99.7	273.3	855.8
	SD	22.4	41.9	48.0	56.5	113.3	266.7
F	MEAN	3.4	12.4	18.3	74.5	255.8	697.0
	SD	5.0	12.0	10.4	14.5	68.5	148.6
G	MEAN	0.0	4.6	22.0	69.5	323.8	827.4
	SD	--	8.3	17.0	39.6	48.2	151.3
H	MEAN	5.0	19.2	35.2	89.2	311.8	831.0
	SD	6.4	12.5	17.0	21.4	56.7	152.4
I	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
J	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
K	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
L	MEAN	-0.5	-10.4	27.0	37.2	348.1	996.6
	SD	33.2	38.0	40.9	47.5	120.5	148.7
TOTAL	MEAN	1.2	11.9	26.9	82.5	304.1	843.7
	SD	13.3	24.4	27.7	37.7	75.2	159.0

TABLE A.8. Mean and Standard Deviation Summary of February Data, Phase 2.
Phase 1 data was reanalyzed using appropriate calibration information.

<u>Contractor</u>		<u>CONTROL</u>	<u>10 MR</u>	<u>20 MR</u>	<u>80 MR</u>	<u>300 MR</u>	<u>800 MR</u>
A	MEAN	0.0	16.6	32.1	86.5	310.2	822.8
	SD	--	19.6	25.9	10.2	23.6	46.4
B	MEAN	0.0	0.0	7.5	58.5	310.6	794.9
	SD	--	--	10.7	5.2	36.2	45.6
C	MEAN	0.5	10.4	18.8	90.0	320.8	820.1
	SD	3.2	3.4	7.1	6.5	7.1	48.8
D	MEAN	0.0	23.6	37.1	113.8	261.6	921.4
	SD	--	16.1	14.3	29.4	147.0	100.0
E	MEAN	1.3	-0.6	19.8	95.5	216.1	920.8
	SD	13.7	16.8	30.0	87.6	77.9	355.6
F	MEAN	4.8	14.1	19.8	81.3	336.1	637.8
	SD	7.5	6.3	11.8	13.0	88.3	245.8
G	MEAN	0.0	0.0	22.8	51.3	332.8	834.0
	SD	--	--	16.7	59.6	20.9	216.1
H	MEAN	8.3	30.2	43.2	111.5	363.6	949.6
	SD	8.6	10.5	15.4	17.1	40.0	72.8
I	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
J	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
K	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
L	MEAN	0.0	-16.0	16.8	24.2	311.1	941.3
	SD	--	46.6	22.7	56.2	25.4	87.1
TOTAL	MEAN	1.6	8.7	24.2	79.2	307.0	849.2

TABLE A.9. Means and Standard Deviations of March Data, Phase 2. There were no 80 mrem irradiations this month.

Contractor		CONTROL	10 MR	20 MR	80 MR	300 MR	800 MR
A	MEAN	0.0	13.8	17.1	--	339.1	967.5
	SD	--	7.6	14.3	--	47.8	68.0
B	MEAN	-1.2	0.0	12.0	--	308.8	802.3
	SD	1.8	0.0	7.9	--	27.3	71.5
C	MEAN	-0.2	9.6	27.1	--	302.3	822.1
	SD	1.3	2.4	14.7	--	38.9	83.1
D	MEAN	0.0	9.4	30.5	--	283.7	784.9
	SD	--	9.9	24.4	--	35.6	50.9
E	MEAN	-12.6	0.5	31.2	--	302.5	763.4
	SD	11.3	36.6	51.5	--	115.8	193.6
F	MEAN	3.7	13.9	14.3	--	221.9	676.6
	SD	3.4	18.2	10.0	--	36.8	117.2
G	MEAN	0.0	2.2	19.7	--	342.4	898.7
	SD	--	5.7	21.6	--	53.5	115.9
H	MEAN	0.8	17.5	37.3	--	312.3	904.5
	SD	1.8	8.5	14.6	--	52.2	95.5
I	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
J	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
K	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
L	MEAN	-1.2	-7.3	50.8	--	389.8	1170.2
	SD	60.5	43.6	38.5	--	160.6	44.0
TOTAL	MEAN	-1.2	6.6	26.7	--	311.4	865.6

TABLE A.10. Mean and Standard Deviation Summary of April Data, Phase 2.

Contractor		CONTROL	10 MR	20 MR	80 MR	300 MR	800 MR
A	MEAN	0.0	22.5	40.2	102.7	301.0	815.6
	SD	--	12.3	11.7	21.4	16.5	74.8
B	MEAN	0.0	10.2	0.0	85.2	301.7	846.1
	SD	--	17.8	--	15.8	22.0	70.2
C	MEAN	0.4	19.7	29.6	83.8	315.6	822.4
	SD	1.5	4.4	2.9	7.0	33.9	69.6
D	MEAN	0.0	55.9	81.3	116.5	307.6	886.6
	SD	--	24.5	42.3	33.4	30.6	154.3
E	MEAN	18.4	70.3	81.8	101.4	272.0	883.4
	SD	29.1	23.8	52.3	45.2	136.2	261.0
F	MEAN	1.5	7.8	23.4	71.1	243.4	760.8
	SD	2.2	7.5	6.8	14.7	18.4	40.4
G	MEAN	0.0	12.8	25.0	76.8	277.8	763.7
	SD	--	10.2	7.4	29.6	23.4	86.1
H	MEAN	5.9	8.5	15.0	78.1	259.0	653.5
	SD	5.4	8.2	7.7	13.1	26.0	31.8
I	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
J	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
K	MEAN	--	--	--	--	--	--
	SD	--	--	--	--	--	--
L	MEAN	-0.2	-7.7	0.3	43.7	301.6	878.4
	SD	14.3	23.1	56.6	44.4	38.3	94.3
TOTAL	MEAN	-3.2	22.2	33.0	84.4	286.6	812.3

TABLE A.11. Accuracy of Phase 2 Neutron Dosimeter Response as Measured by the Relative Bias. Note the improvement over Phase 1 accuracy when the data is reanalyzed given appropriate calibrations. The average total accuracy for all Phase 2 dosimeters now shows an 11% over-response. Most of this is accounted for by the 10 and 20 mrem irradiations.

<u>Contractor</u>	<u>10 MR</u>	<u>20 MR</u>	<u>80 MR</u>	<u>300 MR</u>	<u>800 MR</u>	<u>RANDOM</u>	<u>AVERAGE</u>
A	.74	.38	.22	.08	.09	-.01	.27
B	-.68	-.61	-.06	.02	.02	-.07	-.26
C	.29	.21	.07	.03	.03	-.02	.11
D	1.69	1.16	.45	-.05	.08	.08	.62
E	1.11	.84	.25	-.09	.07	-.15	.38
F	.24	-.08	-.07	-.15	-.13	-.23	-.05
G	-.54	.10	-.13	.08	.03	-.02	-.09
H	.92	.76	.12	.04	.04	-.08	.34
I	--	--	--	--	--	--	--
J	--	--	--	--	--	--	--
K	--	--	--	--	--	--	--
L	-2.04	.35	-.54	.16	.24	.05	-.33
TOTAL	.19	.34	.03	.01	.05	-.05	.11

TABLE A.12. Precision of Phase 2 Neutron Dosimeter Response as Measured by the Coefficient of Variation. Note that the values here are very similar to those of Phase 1. The precision remains essentially the same when recalibration takes place.

Contractor	10 MR	20 MR	80 MR	300 MR	800 MR	AVERAGE
A	.80	.74	.20	.12	.11	.42
B	3.31	1.18	.24	.09	.08	1.07
C	.43	.46	.08	.10	.08	.25
D	.92	.72	.27	.26	.14	.49
E	1.98	1.30	.56	.41	.31	.96
F	.97	.56	.20	.27	.21	.47
G	1.80	.77	.57	.15	.18	.73
H	.65	.48	.24	.18	.18	.36
I	--	--	--	--	--	--
J	--	--	--	--	--	--
K	--	--	--	--	--	--
L	3.65	1.52	1.29	.34	.15	1.46
TOTAL	1.61	.86	.41	.22	.16	.69

TABLE A.13. Regression Analysis of Neutron Dosimeter Response Indicated that the Data Fit a Straight Line with a High Correlation (r) in all Cases. The regression analysis was performed on the given irradiation versus the reported response. Note that the Phase 2 data comes very close to a slope of 1.0 which would be expected when the given and reported values are equal.

Contractor	SLOPE	PHASE 1 INTERCEPT	R	SLOPE	PHASE 2 INTERCEPT	R
A	1.07	6.0	.99	1.07	6.2	.99
B	.92	-7.4	1.00	1.03	-7.7	1.00
C	1.01	3.3	1.00	1.02	3.6	1.00
D	.53	9.0	.98	1.04	13.3	.98
E	.51	2.2	.89	1.04	3.9	.92
F	.33	2.7	.90	.86	1.8	.96
G	.50	5.7	.97	1.04	-2.0	.98
H	.85	7.0	.97	1.02	9.7	.97
I	.73	31.6	.94	--	--	--
J	.35	2.4	.99	--	--	--
K	.95	7.7	.99	--	--	--
L	.92	-20.3	.97	1.27	-26.2	.97

TABLE A.14. The Lower Detection Limit (LDL) is determined by the Standard deviations of the background (0 mrem) and of the LDL combined with the level of acceptable error. Tabulated are the LDLs that result from acceptable of 5%, 10%, and 20% (and are equal). With a 10% acceptable error the average LDL is 58 mrem. If the 2 highest values are neglected (contractors E and L) the LDL is down to 34 mrem. The values for the standard deviations are estimated from control and low irradiation dosimeter data.

Contractor	SD at 0 MR	SD at LDL	LDL at acceptable errors of		
			0.05	0.10	0.20
A	8.0	15.0	45	38	29
B	15.0	21.0	71	59	46
C	3.0	8.0	22	18	14
D	9.5	18.0	54	45	35
E	21.0	60.0	159	133	104
F	6.0	13.0	37	31	24
G	6.5	20.0	52	44	34
H	6.5	15.0	42	35	28
I	6.0	12.0	35	29	23
J	4.0	8.0	24	20	15
K	10.0	6.0	31	26	20
L	30.0	100.	255	213	166
AVERAGE			69	58	45
(excluding E & L)			(41)	(34)	(27)

TABLE A.15. Means and Standard Deviations (SD) of Phase 3 Neutron Dosimeter Irradiated with an Unmoderated Californium Source in a High Scatter Facility. Low scatter results are included for comparison.

Contractor		0 MR	HIGH SCATTER FACILITY			LOW SCATTER
			50 MR	90 MR	250 MR	250 MR
A	MEAN	22.8	85.1	144.7	383.4	252.4
	SD	78.0	39.0	39.2	23.9	27.4
B	MEAN	0.0	71.2	122.3	381.2	215.0
	SD	--	7.0	19.3	13.2	9.2
C	MEAN	-0.6	70.4	135.7	449.5	250.2
	SD	0.6	7.6	9.5	22.3	17.2
D	MEAN	25.6	85.2	138.0	436.0	--
	SD	9.7	25.9	22.7	36.5	--
E	MEAN	136.3	99.1	181.2	327.4	250.0
	SD	83.2	27.4	89.0	41.7	40.6
F	MEAN	6.0	59.3	102.7	335.2	241.9
	SD	5.5	15.6	14.1	59.6	30.6
G	MEAN	5.2	57.9	121.6	380.8	122.5
	SD	1.2	15.2	21.0	54.6	15.3
H	MEAN	6.3	84.2	144.7	343.3	257.1
	SD	6.9	23.6	11.6	38.0	41.7
I	MEAN	--	--	--	--	250.0
	SD	--	--	--	--	41.9
J	MEAN	0.0	20.2	29.5	132.1	68.9
	SD	0.6	5.0	10.2	20.7	12.2
K	MEAN	25.5	109.1	151.6	429.6	--
	SD	18.8	12.8	18.2	11.3	--
L	MEAN	-18.8	90.5	155.3	420.6	262.4
	SD	25.7	20.9	29.0	72.4	25.9
TOTAL	MEAN	18.9	75.4	129.6	363.9	217.0

TABLE A.16. Accuracy of Neutron Dosimeter Response to a High Scatter Facility is reported by contractor and irradiation level with averages for each contractor. The average over-response of all dosimeter at the 250 mrem irradiation level is 38% as compared to the same irradiation in a low scatter environment.

<u>Contractor</u>	<u>.50 MR</u>	<u>90 MR</u>	<u>250 MR</u>	<u>AVERAGE</u>
A	.24	.35	.44	.32
B	.42	.36	.52	.42
C	.42	.51	.80	.53
D	.19	.25	.64	.30
E	-1.74	-.50	-.24	-.94
F	.07	.07	.32	.12
G	.05	.29	.50	.24
H	.56	.54	.35	.51
I	--	--	--	--
J	-.60	-.67	-.47	-.60
K	.67	.40	.62	.55
L	1.19	.93	.76	1.00
TOTAL	.13	.23	.38	.22

TABLE A.17. Precision of Neutron Dosimeter Response to the High Scatter Environment as Reported by Contractor and Irradiation Level

<u>Contractor</u>	<u>50 MR</u>	<u>90 MR</u>	<u>250 MR</u>	<u>AVERAGE</u>
A	.63	.32	.07	.39
B	.09	.16	.04	.11
C	.11	.07	.05	.08
D	.44	.20	.09	.27
E	--	1.98	.22	1.39
F	.29	.15	.18	.21
G	.29	.18	.15	.22
H	.30	.08	.11	.17
I	--	--	--	--
J	.25	.34	.16	.27
K	.15	.14	.03	.12
L	.19	.17	.16	.18
TOTAL	.28	.35	.11	.27

TABLE A.18. Means and Standard Deviations of Neutron Dosimeter Response to Moderated Californium. These irradiations are part of the Phase 3 energy response study.

<u>Contractor</u>		<u>5 MR</u>	<u>10 MR</u>	<u>20 MR</u>	<u>80 MR</u>
A	MEAN	138.7	238.5	452.0	1706.
	SD	37.9	86.3	86.9	64.3
B	MEAN	57.6	129.9	252.5	1046.
	SD	39.8	9.2	17.7	34.8
C	MEAN	58.0	115.0	225.8	853.2
	SD	4.0	9.7	12.3	96.1
D	MEAN	118.2	235.5	441.8	1479.
	SD	15.4	15.5	22.2	367.
E	MEAN	51.4	72.8	146.5	645.5
	SD	10.6	17.9	38.0	159.
F	MEAN	51.1	92.7	178.6	699.9
	SD	10.4	14.1	18.9	149.
G	MEAN	93.8	133.6	240.2	802.3
	SD	43.6	30.8	64.7	122.
H	MEAN	83.6	75.5	149.8	689.4
	SD	34.4	47.7	72.6	112.
I	MEAN	--	--	--	--
	SD	--	--	--	--
J	MEAN	--	20.6	34.6	127.3
	SD	--	6.9	7.4	19.3
K	MEAN	82.5	140.8	244.8	854.6
	SD	3.0	8.1	11.6	52.7
L	MEAN	13.2	178.8	419.4	1841.
	SD	37.2	75.2	57.7	104.
TOTAL	MEAN	74.8	130.3	253.3	977.0

TABLE A.19. Accuracy of Dosimeter Response to Unmoderated Californium as Measured by the Relative Bias. Note that the total accuracy for all contractors is constant across the irradiation levels with an over-response of 1150%.

<u>Contractor</u>	<u>5 MR</u>	<u>10 MR</u>	<u>20 MR</u>	<u>80 MR</u>	<u>AVERAGE</u>
A	26.7	22.8	21.6	20.3	22.6
B	10.5	12.0	11.6	12.1	11.6
C	10.2	10.4	10.2	9.7	10.2
D	22.6	22.6	21.1	17.5	21.2
E	5.3	5.3	5.8	7.1	5.8
F	8.6	8.0	7.8	7.7	8.0
G	17.8	12.4	11.0	9.0	12.3
H	7.5	2.4	4.4	7.1	4.7
I	--	--	--	--	--
J	--	0.8	0.6	0.6	0.7
K	0.7	7.9	8.6	9.3	7.2
L	4.9	18.9	21.0	22.3	17.8
TOTAL	11.5	11.2	11.2	11.2	11.2

TABLE A.20. Means and Standard Deviations of Dosimeter Response to Accelerator Beams of 0.5, 1.9, and 5.0 MeV. Note the change in dosimeter response with energy.

Contractor		0.5 MeV		1.9 MeV		50 MR	5.0 MeV	
		50 MR	100 MR	50 MR	100 MR		100 MR	200 MR
A	MEAN	117.7	227.4	85.8	155.0	51.0	100.2	48.5
	SD	30.2	21.0	24.6	15.0	37.5	55.6	8.6
B	MEAN	56.6	115.2	41.4	102.2	0.0	0.0	33.2
	SD	6.6	6.1	13.8	20.5	--	--	3.8
C	MEAN	104.8	206.6	73.6	146.0	23.3	46.8	49.2
	SD	9.5	19.0	8.6	10.2	8.0	6.2	2.5
D	MEAN	114.4	220.0	79.2	202.4	50.6	79.2	19.8
	SD	26.5	22.0	14.3	50.2	12.5	12.0	12.0
E	MEAN	55.6	91.4	57.8	77.4	17.9	32.2	21.6
	SD	29.5	58.4	22.6	3.0	4.1	11.8	17.5
F	MEAN	78.0	189.4	58.8	120.0	13.4	34.2	27.9
	SD	9.7	18.2	8.0	21.6	8.5	3.9	4.4
G	MEAN	101.8	123.6	87.0	153.8	39.8	54.9	45.0
	SD	18.7	49.0	15.3	26.4	8.5	6.6	6.2
H	MEAN	62.0	215.2	124.1	149.2	39.6	19.8	91.1
	SD	53.5	104.	12.8	43.1	53.8	37.3	85.2
I	MEAN	--	--	--	--	--	--	--
	SD	--	--	--	--	--	--	--
J	MEAN	25.1	44.5	--	--	4.2	-5.2	13.5
	SD	6.9	7.4	--	--	2.2	5.8	4.7
K	MEAN	139.8	172.4	98.6	174.0	32.2	55.3	116.2
	SD	4.4	29.4	6.6	16.9	16.7	6.6	30.4
L	MEAN	121.6	260.2	45.2	119.2	204.4	203.2	134.0
	SD	44.1	75.9	25.2	34.1	194.	112.	35.1
TOTAL	MEAN	88.8	169.6	75.2	139.9	43.3	56.4	54.5

TABLE A.21. Accuracy of neutron dosimeters irradiated by accelerator beams of 0.5, 1.9, and 5.0 MeV. Note the energy dependence of neutron dosimeter response.

Contractor	0.5 MeV		1.9 MeV		5.0 MeV		
	50 MR	100 MR	50 MR	100 MR	50 MR	100 MR	200 MR
A	1.92	1.82	.92	.73	-.24	-.10	-.74
B	.41	.43	-.08	.14	--	--	-.82
C	1.56	1.55	.66	.64	-.50	-.50	-.75
D	1.84	1.73	.77	1.26	.08	-.16	-.90
E	.38	.14	.09	-.24	-.79	-.74	-.88
F	.93	1.35	.24	.30	-.88	-.72	-.85
G	1.53	.54	.94	.72	-.15	-.42	-.76
H	.21	1.51	1.18	.37	-.30	-.86	-.59
I	--	--	--	--	--	--	--
J	-.38	-.45	--	--	-.88	-1.04	-.93
K	1.96	.89	-1.60	-.46	-.37	-.44	-.49
L	1.09	1.77	-.56	.05	.16	-.43	-.49
TOTAL	1.04	1.02	.26	.35	-.39	-.54	-.74

TABLE A.22. Mean and Standard Deviation Summary of Neutron Dosimeter Response to reactor beams of various energies (25 keV, 2.0 keV, and thermal neutrons).

Contractor		CONTROL	25 KeV		2.0 KeV 25 MR	Thermal 25 MR
			50 MR	100 MR		
A	MEAN	89.0	2891.	6925.	5649.	162.8
	SD		1538.	1956.	1087.	260.
B	MEAN	25.0	2268.	4406.	3162.	3440.
	SD		66.7	238.	255.	318.
C	MEAN	76.9	1726.	3204.	2273.	4511.
	SD		189.	312.	144.	533.
D	MEAN	0.0	4472.	8514.	5828.	0.0
	SD		297.	529.	456.	--
E	MEAN	22.9	811.	1201.	864.	-337.
	SD		192.	637.	395.	491.
F	MEAN	10.0	1478.	4084.	2225.	4850.
	SD		291.	438.	206.	51.4
G	MEAN	0.0	451.	439.	535.	491.
	SD		284.	368.	363.	344.
H	MEAN	119.	1687.	3647.	2099.	12090.
	SD		175.	466.	230.	855.
I	MEAN	--	--	--	--	--
	SD		--	--	--	--
J	MEAN	3.8	557.	1073.	649.	76.4
	SD		57.1	124.	68.1	33.5
K	MEAN	106.	1756.	3442.	2365.	8583.
	SD		78.0	162.	106.	439.
L	MEAN	-99.7	3275.	6592.	4969.	140.
	SD		148.	143.	192.	187.
TOTAL	MEAN	32.1	1943.	3957.	2784.	2694.

TABLE A.23. Accuracy of Neutron Dosimeters Irradiated by Reactors Beams of Various Energies. Note the large over-response of dosimeters calibrated to unmoderated Californium to these low energy fields.

Contractor	25 KeV		2.0 KeV 25 MR	Thermal 25 MR
	50 MR	100 MR		
A	55.0	67.4	221.	2.0
B	43.9	42.8	124.	136.
C	32.0	30.3	86.8	176.
D	88.4	84.1	232.	--
E	14.8	10.8	32.6	-15.4
F	28.4	39.7	87.6	18.0
G	8.0	3.4	20.4	18.6
H	30.4	34.3	78.2	478.
I	--	--	--	--
J	10.1	9.7	24.8	1.9
K	32.0	32.4	89.3	338.
L	66.5	65.9	202.	8.6
TOTAL	37.2	38.2	109.	116.

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