Radiation Standards and Calibrations FY-1981 Annual Report

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July 1982

**Prepared for the U.S. Department of Energy
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**Pacific Northwest Laboratory
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by Battelle Memorial Institute**

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RADIATION STANDARDS AND CALIBRATIONS
FY-1981 ANNUAL REPORT

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Richland, Washington 99352

(a) Pennsylvania Power and Light
Allentown, Pennsylvania

FOREWORD

This report presents the research results and status of tasks included in the DOE/RL^(a)-funded "Radiation Standards and Calibrations" subprogram of the Service Assessment Pool programs. During FY-1981, ten laboratory tasks were identified:

1. Maintenance of Standards and Calibrations
2. Maintenance of Process-Control System
3. Error Analysis
4. Development of Process-Control System
5. Neutron Instrumentation
6. Beta Calibrations
7. Calibration Protocols
8. Moderated ²⁵²Cf Capability
9. Instrument Response to High-Energy Photons
10. Pneumatic Source-Transfer System

The results of these tasks are used to support the routine Hanford plant-wide program of instrument and dosimeter calibrations. These programs are managed by the Pacific Northwest Laboratory (PNL)^(b) for the DOE.

(a) U.S. Department of Energy, Richland Headquarters.

(b) Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy.

SUMMARY

The Radiation Standards and Calibrations effort provides the Hanford Plant with radiation calibrations traceable to national standards and provides research necessary for the development of additional calibration capabilities. The scope of the FY-1981 activities included routine calibrations support for the Instrument Calibrations and Evaluations Section, PNL, and development of the calibrations facilities in 318 Building.

Major FY-1981 accomplishments are:

- the development of additional NBS filtered x-ray techniques
- the intercomparison of the PuF_4 and ^{252}Cf fast-neutron sources in 3745A Building, making possible the switch of the Hanford dosimeter calibration source to ^{252}Cf
- the establishment of NBS traceability for the fast-neutron source in 318 Building
- the hookup of remote terminals to realize maximum use of the HP-1000 computer
- the development of the data-control program to record routine instrument repair and calibration services performed
- the study of various neutron sources with available instrumentation to help improve quality assurance procedures in neutron-source calibrations
- the continued development of a high-output beta-irradiation assembly
- the acquisition and study of the beta secondary standard
- the purchase of the hardware necessary to develop a moderated ^{252}Cf capability
- the measurement of the response of routine radiation protection instruments to high-energy photons
- the purchase of a pneumatic source-transfer system to improve the efficiency of the low-scatter facility in 318 Building.

Major FY-1981 research results are:

- The ratio of the response of the Hanford multipurpose personnel dosimeter for routine fast-neutron calibration exposures to its response for the NBS-traceable bare ^{252}Cf exposures is 2.07 ± 0.11 . The difference is due to the energy dependent response of the dosimeter. Because the routine exposure is based on field measurements, it remains the appropriate dosimeter calibration.
- A survey of the calibration errors for routine Hanford dosimeter calibrations indicated that they were much smaller than errors due to TLD selection and processing.
- The reading (R/hr) of the Eberline R0-3B Cutie Pie (side toward source) to capture γ -rays between 2 and 8 MeV was slightly smaller than the 1-cm dose (Rads/hr). The readings were significantly lower than the maximum doses (at depths between 2.5 and 4 cm). The open-window response was typically intermediate between the skin and the 1-cm dose.

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1.0 INTRODUCTION

The Radiation Standards and Calibration program provides technical support for the routine Hanford-wide program for calibration of radiation protection instruments and personnel dosimeters. This support is provided to the Instrument Calibrations and Evaluations Section (Occupational & Environmental Protection Department, PNL) for the Department of Energy through the Service Assessment Pool. The work is performed by the Health Physics Technology Section (Radiological Sciences Department, PNL).

The support encompasses: reviewing calibration standards, regulations, and handbooks; assuring that calibration procedures used are in agreement with technically accepted methods; maintaining basic radioactive sources and instruments that serve as radiological standards; and providing traceability to the National Bureau of Standards (NBS) where possible. In addition, major efforts are being expended to upgrade the 318 calibration facility. This program is necessary to provide a quantitative approach to dosimetry at Hanford and traceability to NBS, and to operate the Radiological Calibrations Facility.

This report focuses on major accomplishments during FY-1981. However, most maintenance and quality assurance efforts involve routine support and only a summary report is provided.

2.0 MAINTENANCE OF STANDARDS AND CALIBRATIONS

Many radioactive sources and radiation-producing machines are routinely used for instrument and dosimeter calibrations. This activity maintained the calibrations of the equipment and carried out quality assurance procedures. Traceability to NBS was maintained or developed for calibrations of beta-particle, photon and neutron sources. In addition to the routine maintenance, additional NBS x-ray techniques were developed; the PuF_4 and ^{252}Cf sources in 3745A Building were calibrated; and, the neutron scatter level for the ^{252}Cf source in the 318 building was studied.

2.1 NBS X-RAY TECHNIQUES

A Picker Gemini control console was added. It is used in conjunction with the Philips x-ray tube to extend our capabilities to include NBS lightly-filtered techniques. The effective energy of the lightly-filtered techniques ranges from 7 keV to 26 keV. The overall range currently available for the filtered techniques is 7 keV to 210 keV.

2.2 CALIBRATION OF THE PuF_4 AND ^{252}Cf SOURCES IN 3745A BUILDING

Historically, the PuF_4 calibration exposure time was set to reproduce measurements made in the field. However, because the fast-neutron source for routine personnel-dosimeter calibrations was to be changed to ^{252}Cf , a study was made of the neutron sources in 3745A Building. The first goal of the study was to relate the response rates for the Hanford multipurpose personnel dosimeter to the calibration exposure for the PuF_4 source and to an exposure for the ^{252}Cf source in 3745A. The result is contained in a report to the PNL dosimetry committee. A second goal was to relate the response of the Hanford dosimeter for the 3745A sources to the response for the NBS-traceable ^{252}Cf Source in 318 Building. A report of this investigation is included in the appendix.

Fast-neutron calibrations provided for the routine dosimetry system currently use conditions specified in the report to the dosimetry committee. All

other fast-neutron calibrations done in 3745A Building use the Tissue-Equivalent Proportional Counter (TEPC) calibrations listed in Table 2 of the appendix.

2.3 EFFECTS OF NEUTRON SCATTER LEVELS FOR THE ^{252}Cf SOURCE IN 318 BUILDING

Two steps are required to establish traceability to NBS for a fast-neutron source. The first is to obtain an NBS calibration of the emission rate for the source. The second is to measure the effects of scattered neutrons in the facility where the source is used. Neutrons scattered from the room surfaces (room return), the air, and the source-support hardware have a much lower energy spectrum than the neutrons emitted from the source. Each type of instrument or dosimeter could have a different response to the low-energy neutrons.

Because room return varies with room dimension, measurements were made in the 318 facility to characterize room return for the Hanford dosimeter and the TEPC. The response of the Hanford dosimeter depends on neutron energy (Endres et al. 1981) and thus can be greatly influenced by room return. Data was taken at several distances from the source. We used the approximation that at the center of the room the level of scattered neutrons is constant. After the dosimeter response has been corrected for air scatter, the portion that does not decline with distance according to the inverse-square law is called room return. The percent increase of the response relative to the unscattered neutrons from the source (or "free field") depends on distance squared. For the Hanford dosimeter, the 318 room return correction is $10\% \text{ m}^{-2}$ compared with $20\% \text{ m}^{-2}$ for the NBS ^{252}Cf facility. The total scatter factors at 50 cm for 318 and NBS are 6% and 8%, respectively.

3.0 MAINTENANCE OF PROCESS-CONTROL SYSTEM

This activity helps maintain and operate the process-control system, which includes the HP-1000 computer and peripherals. The computer software has been kept current through the software maintenance agreement with Hewlett-Packard. Four system regenerations have been performed to incorporate the software revisions. Three new modems were installed by the General Telephone Company to allow additional remote terminals in 3745 Building to be installed.

Our computer hardware maintenance agreement with Hewlett-Packard was terminated after the first year of operation, in accordance with Battelle policy. We now have a hardware maintenance agreement with the Battelle Craft and Operations Services Department.

4.0 ERROR ANALYSIS

The exposure or dose delivered during the calibration of dosimeters or instruments has many sources of uncertainty. If NBS traceable, there is an uncertainty in the application of the primary standards used and in the NBS measurement techniques. Additional areas of uncertainty include calibration measurement errors, uncertainties associated with exposure geometry errors and timing (or monitor detector) errors. This section contains an analysis of the exposure errors for the ^{137}Cs source; a discussion of the dominant errors for fast-neutron calibrations of Hanford multipurpose personnel dosimeters; and a summary of error interactions between the four calibrations performed for the Hanford dosimeter.

4.1 BEAM UNIFORMITY AND EXPOSURE REPRODUCIBILITY FOR THE ^{137}Cs SOURCE IN THE 318 BUILDING

Beam uniformity for the ^{137}Cs irradiator was measured with an ionization chamber and confirmed with personnel dosimeter measurements. The irradiation assembly shown in Figure 1 has a lead collimator and a support assembly for the plexiglass phantom. Dosimeters are typically irradiated on the phantom at a source-to-phantom-surface distance of one meter. Ionization-chamber readings were taken for a matrix of points ranging over the face of the phantom. Paired on-phantom/in-air measurements were taken. A chamber measurement was taken at a location immediately in front of the phantom and then repeated with the phantom removed. Figures 2 and 3 show the matrix of measurements taken. The rectangle outline represents the phantom placement. The measured values are listed just below the measurement position (indicated by a large dot). All measurements are normalized to the central position. Both sets of measurements have a region near the center that has good uniformity. The presence of the phantom does not have a significant effect on uniformity. The useful irradiation region is inside the approximately 10-cm x 10-cm rectangle shown in dotted lines in Figure 3. Dosimeters to be exposed are mounted with their sensitive position within this rectangle. The net relative range for dosimeter exposures is ~2%.

FIGURE 1. ^{137}Cs Irradiation Assembly

The general behavior of the nonuniformity was checked using Hanford dosimeters (see Figure 4). Measurements made on the outer edge of the phantom allowed the detectable difference from the center position to be confirmed. Given the approximate 2% uncertainty in each edge reading, the measurements are consistent with the ionization-chamber readings in Figure 3. The dosimeters used were calibrated for relative efficiency using routine ^{137}Cs exposures.

FIGURE 2. In-Air Ionization Chamber Readings for the ^{137}Cs Source. The dots mark the chamber positions. The readings are normalized relative to the center position. Phantom dimensions are 30 cm x 30 cm x 15 cm.

Exposure reproducibility measurements were taken using tightly-screened thermoluminescent dosimeters (TLD) in hand-loaded Hanford dosimeters. Each irradiation group contained two Hanford dosimeters with two TLD's per position, for a total of 20 TLD's. Dosimeter positions one, two and five contained TLD 700's and position three and four contained TLD 600's. A total of fifteen groups were taken to three exposure levels in five separate trials. The exposure levels allowed a determination of linearity and the five trial exposures determined reproducibility. The measurement uncertainty for the TLD system (primarily the TLD selection variances) was estimated from the TLD fluctuations

FIGURE 3. On-Phantom Ionization Chamber Readings for the ^{137}Cs Source. The dots mark the chamber positions. The readings are normalized relative to the center position. The dotted line encloses the useful irradiation region. The phantom dimensions are 30 cm x 30 cm x 15 cm.

in each group. The reproducibility uncertainty was derived by subtracting the TLD selection variances from the variances of the exposure group readings.

Tests were performed to determine the linearity of the exposure. Results are shown in Table 1. Columns 2-6 contain the mean TLD readings ($\bar{X}$) and the sample standard deviations (S) for each dosimeter position. The linear regression fits show that the data is highly correlated. The average zero intercept for the five positions is -1 mR, which is not significantly different from zero. The exposure timing is linear with no zero-level offset.

FIGURE 4. Edge Effects for ^{137}Cs Irradiations. Dosimeter placement on a phantom is shown, along with the relative response.

The results for the reproducibility measurements are given in Table 2. The mean standard deviations for the TLD's are averages of the estimated values for each group. They agree with the approximate screening widths of $\pm 3\%$ for TLD 700's and $\pm 5\%$ for TLD 600's. The mean total standard deviation is the average value for each group, with the TLD 700 and TLD 600 positions averaged independently. The TLD standard deviation of the (group) mean can be removed from the total standard deviation using:

$$S_R^2 = S_G^2 - S_{\text{TLD}}^2/4$$

where S_R is the standard deviation for exposure reproducibility, S_G^2 is the

TABLE 1. Linearity of ^{137}Cs Irradiations

Exposure, mR ^(a)	Hanford Dosimeter Positions ^(b)				
	1 (nC)	2 (nC)	3 (nC)	4 (nC)	5 (nC)
150 $\bar{X}$ =	79.6	75.9	68.9	69.2	77.6
S =	1.5	0.6	3.0	2.2	1.2
300 $\bar{X}$ =	158.9	156.5	137.0	138.3	155.2
S =	2.0	4.2	3.7	2.4	1.0
537 $\bar{X}$ =	279.7	272.6	247.2	246.0	281.2
S =	5.7	11.4	9.2	8.4	9.2
Parameter ^(c)					
A, mR	-5.5	-3.1	1.5	-2.0	3.7
B, mR/nC	1.94	1.97	2.17	2.20	1.90
r	1.000	1.000	1.000	1.000	1.000

Mean zero intercept = -1.1 mR

- (a) $\bar{X}$ = mean reading for the five groups per exposure. S = sample standard deviation per group. For an estimate of the standard deviation of the mean, divide S by $\sqrt{5}$.
- (b) Positions 1, 2 and 5 contain TLD 700's. Positions 3 and 4 contain TLD 600's.
- (c) $y = A + Bx$ and r is the sample correlation coefficient.

TABLE 2. Reproducibility of ^{137}Cs Irradiations

	Percent Standard Deviation	
	TLD-700	TLD-600
TLD Readings (S_{TLD})	3.0%	4.5%
Reproducibility Groups (S_G) (4 TLD's)	2.0%	3.2%
Exposure Reproducibility (S_R) ^(a)	1.3%	2.2%
Average (95% Confidence Limits)	1.5% $\begin{pmatrix} -0.4 \\ +0.8 \end{pmatrix}$	

$$(a) S_R^2 = S_G^2 - S_{\text{TLD}}^2/4$$

standard deviation for the sample groups and S_{TLD} is the standard deviation for the TLD readings. The standard deviation for exposure reproducibility calculated using TLD 700's and TLD 600's is mutually consistent. The average value of 1.5% is shown in the last row of Table 2. The error limits were estimated using χ^2 distributions with 36 and 24 degrees of freedom for the TLD 700's and TLD 600's, respectively.

4.2 FAST-NEUTRON CALIBRATION VARIABILITY FOR PERSONNEL DOSIMETERS

Fast-neutron calibrations are performed routinely for the Hanford multi-purpose personnel dosimeter. Calibration-factor errors are dominated by dosimeter response variabilities due mainly to dosimeter design, TLD efficiency acceptance widths and the dose-equivalent calculation algorithm (Thorson and Endres 1981). This section is an analysis of calibration-factor variations based on data from routine calibrations.

Routine dosimeters are processed in batches determined by the schedule of dosimeter exchanges in the field. The reading of a batch of dosimeters is called a run, which can include several calibration sets. Each calibration set contains six fast-neutron calibration dosimeters, which are more tightly screened for uniform response than field dosimeters. Each set of six calibration dosimeters is exposed together. We define the fast-neutron response function as:

$$R(\text{FN}) = R_4 - K_6 \cdot R_2 - K_5 \cdot (R_3 - R_4)$$

where R_2 , R_3 , and R_4 are TLD readings and K_5 and K_6 are calculated from the penetrating and slow-neutron calibration sets (Fix et al. 1981):

$$K_5 = (R_4 - K_6 \cdot R_2) / (R_3 - R_4) \quad (\text{from slow-neutron exposure})$$

$$K_6 = R_4 / R_2 \quad (\text{from penetrating exposure}).$$

Values for the fast-neutron response function of calibration sets spanning almost a year are given in the second column of Table 3. The values vary by a factor of two, mainly due to TLD-reader normalization changes. The

TABLE 3. Fast-Neutron Calibration Data (PuF₄ Source, Reader α2, 1980)

Calibration Set ^(a)	Fast-Neutron Response Function, 1 Rem	Penetrating Calibration, 1 R ¹³⁷ Cs	Ratio FN/P	Fast-Neutron % Standard Deviation Per Dosimeter	K5 ^(b)	K6 ^(c)
Feb1	951	1430	0.665	32	0.667	0.852
Feb2	1091	1345	0.811	23	0.686	0.851
Mar1	1042	1344	0.775	15	0.725	0.867
MarQ1	1092	1421	0.768	20	0.772	0.904
MarQ2	1389	1683	0.825	21	0.806	0.958
Apr1	1508	1715	0.879	17	0.765	0.976
May1	1292	1429	0.904	27	0.882	0.877
Jun1 ^(d)	1188	1621	0.733	28	0.787	0.903
Aug1	1560	1755	0.889	21	0.856	0.967
Aug2	1385	1733	0.799	20	0.831	0.924
Sept1	1252	1722	0.727	18	0.857	0.925
Sept2	1621	1643	0.987	14	0.922	0.979
SeptQ1	1499	1747	0.858	7	0.810	0.966
SeptQ2	1577	2009	0.785	26	0.762	0.912
SeptQ3 ^(e)	969	2148	0.451	15	0.736	0.872
Oct1	1832	2091	0.876	20	0.762	0.874
Oct2	1656	2122	0.780	19	0.763	0.906
Oct3	1667	2223	0.750	17	0.815	0.878
Nov1	1818	2026	0.897	15	0.713	0.776
Nov2	1511	2030	0.744	20	0.752	0.822
Dec1	1761	2228	0.790	11	0.768	0.871
Dec2	1613	2140	0.754	20	0.774	0.869
DecA1	1631	2163	0.754	24	0.914	0.941
DecCU1	2079	2293	0.907	39	0.933	0.938
Mean			0.811	20.4%	0.794	0.900
% SD per Calibration Set			9.4%	8.3%	9%	6%

(a) The types of runs are quarterly (Q), annual (A), cleanup (CU) and monthly (no letter). There are six calibration dosimeters per set.

(b) Calculated from slow-neutron calibration dosimeters.

(c) Calculated from penetrating calibration dosimeters.

(d) An outlier was omitted.

(e) Given one-half of the calibration exposure. Omitted from average.

normalization changes are removed when the response functions are divided by the R4 reading from the penetrating calibration (Column 3), which was read at the same time. The ratio is given in Column 4. The estimated standard deviation per calibration set is 9.4%. Column 5 lists the estimated percent standard deviation per dosimeter for each calibration set. The mean value is the contribution to the total error from variations not due to calibration reproducibility. This error is due to the response variabilities of individual dosimeters.

The estimated standard deviation per calibration set due to response variabilities is 8.3%. The difference between this value and the total estimated standard deviation in Column 4 (9.4%) can be attributed to variations in the K5 constant (Column 6) and (to a lesser extent) in the penetrating R4 reading. Errors due to dosimeter exposure variations are much smaller than the contribution from individual dosimeter-response variations.

One of the calibration sets (SeptQ3) has a response that is not consistent with the rest of the sets. All dosimeters in this set consistently read approximately a factor of two low. The exposure records indicate that one of the sets only received one of the two overnight exposures (a total of 33.3 hrs) typical of the PuF₄ calibration runs.

4.3 ERROR INTERACTIONS

Because calibration exposures are not performed with pure nonpenetrating, penetrating, slow-neutron or fast-neutron sources, subtractions of unwanted contributions are required. Penetrating-radiation corrections are made to the nonpenetrating and fast-neutron calibration exposures using constants K2(=R1/R2) and K6. Slow-neutron corrections are made to fast-neutron calibration exposures using K5.

Contributions to the calibration errors due to these corrections are shown in Table 4. The formula was derived using the calibration constants,

$$K3 = \frac{(R1 - K2 \cdot R2)}{D} \quad (\text{nonpenetrating})$$

and

$$K7 = \frac{R4 - K6 \cdot R2 - K5 \cdot (R3 - R4)}{DE} \text{ (fast neutrons)}$$

where D is the calibration dose for the nonpenetrating calibrations and DE is the calibration dose equivalent for fast-neutron calibrations. These constants are the inverse of C2 and C5 (Fix et al. 1981).

Estimates of the contributions to the errors for the fast-neutron calibrations were made using average values for the TLD readings and the K constants, and the observed fluctuations in K5 and K6 (Columns 6 and 7 of Table 3). Uranium-slab nonpenetrating calibration exposures currently used have a sufficiently small penetrating component to make the error contribution negligible.

The contribution to the fast-neutron calibration error due to K5 of 4% is smaller than the 8% contribution due to dosimeter fluctuations (Table 3, Column 5). The net effect of the K5 fluctuations is to increase the calibration error from 8% to 9%, which is consistent with the observed total error (Table 3, Column 4).

The contribution to the random error due to unwanted exposure subtractions will be small provided the subtractions are small. There is also a bias error due to the nonidentity of unwanted exposure radiations and the corresponding calibration type. This error remains uncorrected. For instance, the signal

TABLE 4. Calibration Interactions

		<u>Penetrating</u>	<u>Slow Neutron</u>
Contribution to Calibration Errors	Non- penetrating	$-\frac{K2 \cdot R2}{K3 \cdot D} \frac{S_{K2}}{K2}$ (negligible)	
	Fast Neutron	$-\frac{K6 \cdot R2}{K7 \cdot DE} \frac{S_{K6}}{K6}$ 0.5%	$\left[\frac{K5 \cdot (R3 - R4)}{K7 \cdot DE} \right] \frac{S_{K5}}{K5}$ 4%

The S_K 's are the estimated standard deviations for the K constants.

received during fast-neutron exposures that is due to slow neutrons is not necessarily represented by the slow-neutron calibration exposure (from the sigma pile). The room-scattered slow neutrons do not uniformly reach the dosimeter due to the phantom backing required for the fast-neutron exposures. This probably contributes a several percent bias error to the fast-neutron calibration constants.

5.0 DEVELOPMENT OF PROCESS-CONTROL SYSTEM

A second control console and cathode transformer were added to the x-ray system this year. Thus, each x-ray tube is connected to its own control system. This eliminates the need to re-adjust the console every time a different tube is used. Since the consoles are nearly identical, it also supplies a back-up console if either console fails. The analog meters are being replaced by digital meters with binary-coded decimal computer outputs. This allows more precise data input to the computer-control program. One of the consoles has been modified to include the digital meters. We are awaiting parts to modify the other console. Two new digital input/output devices have been added to the process-control system to accommodate these additional inputs.

The x-ray room temperature and pressure instruments were connected to the processor interface of the computer to allow automatic temperature/pressure corrections for x-ray exposures.

The HP-1000 computer will be used to record and follow the flow of instruments through the Instrument Calibrations and Evaluations Section laboratories. Software was written to allow development of the data base for instrument control.

6.0 NEUTRON INSTRUMENTATION

A variety of instruments are available for measuring neutrons, but most have strong energy-dependent responses. Because of the various types of sources and differing exposure-room environments, neutron source spectra can vary widely. An instrument is needed to serve as a "transfer standard" to compare calibrations for sources with different energy spectra. Therefore, the purpose of this task was to investigate the feasibility of using an extrapolation chamber for neutron calibrations. The chamber would be manufactured with plastic that is tissue-equivalent for neutron exposures.

The characteristics of several neutron sources were studied. Measurements were taken with the Hanford multipurpose personnel dosimeter, tissue-equivalent proportional counters, and long counters. These results are contained in the report in the appendix. This effort will continue with the testing of the response of existing extrapolation chambers to the neutron sources.

7.0 BETA CALIBRATIONS

The quality of beta-source calibrations is not as highly developed as photon-source calibrations. Beta sources are calibrated in terms of absorbed dose, measured by extrapolation chambers. The procedure for establishing NBS traceability is to obtain NBS extrapolation-chamber measurements on a standard beta source; to calibrate the user extrapolation chamber(s) using the calibrated source; and to calibrate beta sources in routine use with the calibrated extrapolation chamber.

Beta-source calibration biases are caused by 1) variations in the source-detector geometries, 2) differing chamber response to spectral changes due to source construction, 3) varying air density and humidity, and 4) varying extrapolation chamber design. These limitations are particularly apparent when different source types are compared. To aid in the identification of calibration biases, we purchased a set of secondary beta standards. The standards were calibrated by the Physikalisch-Technische Bundesanstalt (PTB)^(a) in the same geometry in which they are to be used. The calibration procedure included corrections for air density and humidity. These sources are used as an independent check of our calibration procedures.

This section will first describe the irradiation assembly developed for routine beta-source exposures. Next, the source-calibration procedures and status will be discussed. The secondary standard will be described in the final subsection.

7.1 IRRADIATION ASSEMBLY

The irradiation assembly developed for beta-particle calibrations is shown in Figure 5. The source is attached to a remotely controlled antenna. It can be moved down inside the protective shield or up into the irradiation position. The plexiglass phantoms are mounted on aluminum support stands. Dosimeters are typically mounted on the front face of the phantoms. When filters are required, they are hung from the cords attached to the metal posts.

(a) The National Bureau of Standards for the Federal Republic of Germany.

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FIGURE 5. Irradiation Assembly for Beta-Particle Calibrations

Several sources can be mounted on the tip of the antenna. We have three $^{90}\text{Sr}/^{90}\text{Y}$ sources: an NBS-calibrated button source, a one-inch-diameter spherical source, and a large planar source. Other sources available include ^{85}Kr , $^{106}\text{Ru}/^{106}\text{Rh}$ and ^{147}Pm .

Measurements were made with an ionization chamber to determine the level of scattered radiation from the equipment supports and the room walls. Scatter levels were not significant at the dosimeter irradiation positions. Further tests are needed to detect the presence of scattered electrons of very low energy.

7.2 CALIBRATION

The beta-particle sources are calibrated and compared using a tissue-equivalent extrapolation chamber (TEEC). All beta-particle sources are calibrated at a depth of 0.007 cm, the depth of the shallow dose specified in BSR N13.11 (1981). The front window on the extrapolation chamber was designed so that the front collecting electrode was at the shallow depth.

The NBS-calibrated ^{90}Sr button source was used to compare our extrapolation-chamber measurements to the NBS measurements. Because NBS calibrations were made using an extrapolation chamber with a very thin front window (0.0007 cm) our data had to be corrected for the dose buildup at 0.007 cm (~6%). After the correction was made, our extrapolation-chamber measurement was 2% higher than the NBS calibration. This was in sufficient agreement for us to use our chamber to calibrate other beta sources, without requiring an additional correction factor.

7.3 SECONDARY STANDARDS

A set of secondary standards for the absorbed dose of beta radiations was purchased. They were manufactured by Buchler GmbH & Co. in cooperation with the PTB. The set is composed of four sources: low-level sources of ^{147}Pm , ^{204}Tl and $^{90}\text{Sr}/^{90}\text{Y}$ and a high-level $^{90}\text{Sr}/^{90}\text{Y}$. Calibration documents from the PTB were provided.

The absorbed dose rates for PTB-calibrated and NBS-calibrated sources were compared using the high-level $^{90}\text{Sr}/^{90}\text{Y}$ PTB source, the NBS-calibrated $^{90}\text{Sr}/^{90}\text{Y}$ button source and the TEEC. The absorbed dose to tissue measured by the TEEC was 10% higher than the PTB calibration report. The resulting discrepancy between the NBS-traceable calibration and the PTB calibration is 8%. Further investigations will better establish the reproducibility of our chamber measurements and identify additional causes of the discrepancy. The performance of our TEEC compared to the other PTB-calibrated sources will also be determined.

8.0 CALIBRATION PROTOCOLS

Several changes in the source geometry environment will occur when the routine dosimeter and instrument calibrations are moved from Building 3745 to Building 318. Those identified for study were 1) changing the fast-neutron source environment in 3745A Building for the environment in 318 Building, and 2) investigating the effects of using ^{137}Cs and a neutron source in source wells. The study of the source wells will be done in FY-1982.

8.1 CHANGE OF THE FAST-NEUTRON SOURCE ENVIRONMENT

The relative responses of the Hanford dosimeter to the fast-neutron sources in Buildings 3745A and 318 were measured. The main difference between the facilities is the size of the irradiation rooms. The 3745A room is small, producing a high scattered-neutron background. The 318 irradiation room is large, producing a much lower background. The advantages of using the low-scatter facility in Building 318 are 1) it is easier to establish traceability to NBS (see Section 2.3 for the discussion on NBS traceability for the 318 irradiation room), and 2) there are less response variations between neutron detection devices caused by the scattered neutrons. Details of the fast-neutron source measurements are contained in the Appendix.

The ratio of the dosimeter response for the field-based PuF_4 exposures to the NBS-traceable 318 exposures is 2.07 ± 0.11 (taken from Table A.10). The ^{252}Cf source in 3745A Building has a calibration exposure time that was matched to the field-based PuF_4 exposures and a calibration based on TEPC measurements. The ratio between 318 exposures and the TEPC-calibrated exposures for the 50-cm positions is 1.46 ± 0.20 (taken from Tables A.8 and A.9).

9.0 MODERATED ^{252}Cf CAPABILITY

Hardware was purchased to allow the development of the capability for moderated ^{252}Cf irradiations. The draft standard BSR N13.11 (1981) specifies the use of heavy-water moderated ^{252}Cf exposures. The hardware closely follows the NBS design (Schwartz and Eisenhauer 1980). The only modifications required were those to make it compatible with the pneumatic source-transfer system. This capability will allow the use of the same ^{252}Cf source for both bare and moderated irradiations, with only the mounting or dismounting of the moderator required.

The moderator is composed of a 30-cm-diameter stainless-steel sphere filled with heavy water. Stainless-steel tubing inserts welded to the sphere accept the source irradiation assembly and allow for the reproducible positioning of the source at the center of the sphere. A cadmium covering over the surface of the sphere absorbs the thermal neutrons generated in the moderator.

10.0 INSTRUMENT RESPONSE TO HIGH-ENERGY PHOTONS

Radiation-protection instruments were irradiated with high-energy capture gamma rays at the Texas A&M TRIGA reactor. Instrument responses in mR were compared to the absorbed dose rates in tissue measured with a TEEC. A Victoreen Radector with an external chamber and an Eberline RO-3B Cutie Pie were irradiated at various orientations to the beams with and without back-scatter from a phantom. In addition, self-reading pocket dosimeters, manufactured by Dosimeter Corporation of America (DCA), and capacitance-type pocket dosimeters, manufactured by Victoreen, were taped to a phantom and irradiated. The front face of the TEEC was used as the phantom.

Capture gammas were generated when neutrons from the reactor core scattered and thermalized in a graphite box and interacted with target material. Targets consisting of silicon dioxide, sulfur, carbon steel and water produced Si, S, Fe and H capture gammas, respectively (Holland and Neff 1981). Principal photon energies and approximate abundances are included in Table 5. A significant but undetermined contribution from aluminum capture gammas is present due to the use of aluminum in structural materials and target encapsulations.

A beam port lined with borated paraffin provided a highly collimated photon field that was free of measurable neutron contamination (Holland and Neff 1981). Instruments were irradiated at a distance of 1.6 m from the opening of the beam port. Extrapolation-chamber measurements were obtained for a variety of buildup thicknesses. The instrument results were compared to measured absorbed dose rates at 0.007 cm (skin), 0.94 cm and $d_{\max}$, where $d_{\max}$ is the depth of maximum dose in tissue. Values of absorbed dose at 0.94 cm closely approximate the 1-cm-depth dose and are of the most interest for general health physics usage. Since reactor power was lowered from 1 MW to 400 kW or 250 kW for some of the instrument irradiations, an ionization chamber was used to normalize extrapolation-chamber results.

TABLE 5. Principal Capture-Gamma Photon Energies(a)

Target	Photon Energies, Mev	Approximate Abundance, %
H	2.22	>97
Fe	7.63	34
	1.73	11
	1.61	10
Si	7.20	10
	6.38	14
	4.93	61
	3.54	64
	2.09	20
	1.27	20
S	5.42	60
	4.87	11
	3.22	20
	2.93	15
	2.38	34
	0.84	60
Al	7.72	17
	1.78	88

(a) Bartholomew, et al., 1967

Results for survey instrument irradiations are given in Tables 6 and 7. Even though the roentgen is not recommended for use above 3 MeV, instrument results are left in units of exposure because the conversion from roentgen to rem is not supported by standards (ICRU 14 1969) at the higher energies. If exposure readings are used to estimate the 1-cm-depth dose, "cutie pie" results are low by 8-16% (instrument axis perpendicular to beam, no phantom). The presence of a phantom improved the dose estimation for the hydrogen-target beam. However, the doses for the sulfur and iron capture-gamma beams were overestimated by 11% and 27%. Use of the open-window configuration provided estimates that were much lower than the 0.94-cm-depth dose and much higher than skin doses. Radector results are available only for the H, Si and S beams with

TABLE 6. "Cutie Pie" Response to Capture Gammas^(a)

Target	TEEC Assigned Dose Rates, Rads/hr			CP Readings, R/hr		
	Skin 0.007 cm	0.94 cm	Maximum Depth Dose	Side, With Phantom	Side, Without Phantom	Open Window
H	1.215	4.528	5.375	4.7	3.9	3.2
Fe	0.423	1.810	2.647	2.3	1.6	1.9
Si	0.319	1.228	1.563	1.1	1.1	0.8
S	0.676	2.804	3.526	3.1	2.6	1.9

(a) Corrected for temperature and pressure.

Maximum depth doses occurred at 2.65 cm for the hydrogen, silicon and sulfur beams, and 3.81 cm for the iron beam.

TABLE 7. Victoreen "Radector" Response to Capture Gammas

Target	TEEC Assigned Dose Rates, Rads/hr			Radector Response, R/hr ^(a)
	Skin 0.007 cm	0.94 cm	Maximum Depth Dose	
H	1.215	4.528	5.375	6
Si	1.284	4.939	6.285	5
S	0.676	2.804	3.526	4

(a) Taken through side of chamber with phantom.

the detector in front of the phantom. The readings overestimated the 0.94-cm dose for the H and S beams by 30% to 40%, but provided a good estimate with the Si beam.

Pencil dosimeter readings are summarized in Tables 8 and 9. The precision was quite good; the largest sample standard deviation (sample sizes of 4) was 7.5%. Dosimeters from DCA provided estimates 26%, 35%, 30% and 37% lower, respectively, than the 1-cm-depth doses for H, Fe, Si and S. Victoreen dosimeter readings are somewhat lower, underestimating the 1-cm-depth dose by approximately a factor of two.

TABLE 8. Response of DCA Pencil Dosimeters (Self Reading)
to Capture Gammas

<u>Target</u>	<u>Dosimeter ID</u>	<u>Dosimeter Response, mR</u>	<u>TEEC Assigned Doses, mrad</u>		
			<u>Skin 0.007 cm</u>	<u>0.94 cm</u>	<u>Maximum Depth Dose</u>
H	40158	200			
	40159	200			
	1030255	217			
	1030256	197			
	Mean	<u>204</u>	79	274	344
Fe	40158	157			
	40159	159			
	1030255	155			
	1030256	<u>157</u>			
	Mean	<u>157</u>	56	243	353
Si	40158	82			
	40159	89			
	1030255	82			
	1030256	<u>79</u>			
	Mean	<u>83</u>	31	119	152
S	40158	162			
	40159	162			
	1030255	188			
	1030256	<u>179</u>			
	Mean	<u>173</u>	66	274	344

TABLE 9. Response of Victoreen Pencil Dosimeters to Capture Gammas

<u>Target</u>	<u>Dosimeter ID</u>	<u>Dosimeter Response, mR</u>	<u>TEEC Assigned Doses, mrad</u>		
			<u>Skin 0.007 cm</u>	<u>0.94 cm</u>	<u>Maximum Depth Dose</u>
H	4544	46			
	24685	41			
	28602	45			
	21508	43			
	Mean	<u>44</u>	23	84	100
Fe	4544	55			
	24685	48			
	28602	50			
	21508	50			
	Mean	<u>51</u>	24	104	152
Si	4544	62			
	24688	66			
	28602	67			
	21508	70			
	Mean	<u>66</u>	31	119	152
S	4544	35			
	24685	36			
	28602	40			
	21508	40			
	Mean	<u>38</u>	19	78	99

11.0 PNEUMATIC SOURCE-TRANSFER SYSTEM

A pneumatic source-transfer system was ordered from Reactor Experiments, Inc. It will be installed in the low-scatter irradiation room in the 318 Building. This system will improve facility usefulness by permitting the use of any of four sources in either of two irradiation stations. The sources will be stored in existing storage tubes in the concrete floor. One of the irradiation positions will be mounted on the existing tripod stand in the approximate center of the room. The other irradiation position will be located at about eye level near one end of the room.

APPENDIX

THE HANFORD DOSIMETER FAST-NEUTRON RESPONSE TO ^{252}Cf AND PuF_4 SOURCES

APPENDIX

THE HANFORD DOSIMETER FAST-NEUTRON RESPONSE TO ^{252}Cf and PuF_4 SOURCES

The fast-neutron calibration for the Hanford multipurpose personnel dosimeter is based on field measurements taken about 1970. Field dose rates were measured at numerous locations throughout the Hanford site using TEPC's. The dosimeter response to the field dose rates and to exposures from a PuF_4 source were matched to yield a calibration exposure time. The PuF_4 source was used to calibrate the Hanford dosimeter until mid 1981, when the routine calibration work was shifted to a ^{252}Cf source in the same exposure room. The dosimeter responses to the sources were matched, maintaining traceability to the field measurements.

Before the PuF_4 source was removed from 3745A, its dose rate was compared to that of the ^{252}Cf source in the 318 Building using both the TEPC and Hanford dosimeters. The 318 source calibration is traceable to the NBS, providing a comparison between the current fast-neutron calibration and a traceable calibration for unmoderated ^{252}Cf . This report contains the data taken to determine the relative response of the Hanford dosimeter to the PuF_4 and ^{252}Cf sources in 3745A Building and the ^{252}Cf source in 318 Building.

FAST-NEUTRON RESPONSE EQUATIONS

A detailed description of the dosimeter design is reported by Fix, et al. (1981). We define the dosimeter fast-neutron response as a function of the radiation source,

$$R(\text{source}) = R4 - (K6 \times R2) - (K5 \times (R3 - R4))$$

where R2, R3 and R4 are dosimeter TLD readings, and K6 and K5 are constants determined from the ^{137}Cs and slow-neutron calibrations, respectively. The fast-neutron dose-equivalent formula is

$$\text{FN} = \text{C5} \times \text{R (field source)}$$

where

$$\text{C5} = \frac{1000 \text{ mrem (field calibration)}}{\text{R (field calibration)}}$$

We assume that $\text{R (PuF}_4\text{)} = \text{R (field calibration)}$ for the 33.3-h calibration exposure time.

IRRADIATION GEOMETRIES

The irradiation geometries are listed in Table 10. The PuF_4 calibration geometry has two opposing phantoms 35 cm from the source. The floor and the south wall are the closest potential large-backscatter sources.

Measurements were taken in four geometries for the 3745A ^{252}Cf source. All but the 50-cm position used two phantoms in the northwest and southwest directions. The two geometries investigated for the 318 ^{252}Cf source were 35 cm (two phantoms) and 50 cm (one phantom). The distances to the concrete floor and walls are listed in the last column. The smaller 3745A irradiation room produces more neutron scattering.

Table 11 contains the TEPC measurements for the three sources. The PuF_4 measurements were taken with the detector in the east direction. Source isotropy was checked by rotating the source with the detector at the 45-cm-east position. The dose-rate dependence on distance does not follow an inverse-square relationship, in part due to the large size of the source (a cylinder 10 cm in diameter by 12 cm in height).

The 35-cm measurements for the 3745A ^{252}Cf source were taken with the opposite phantom in place. The dosimeter exposures were done using the average of the two readings. Measurements were taken with and without a phantom behind

TABLE 10. Irradiation Geometries

Source	Phantoms	Source-to Surface Distance	Direction	No. of Dosimeters per Phantom	Source-to-Concrete Distance
PuF ₄ α2 3745A Bldg.	two 24 cm dia x 22 cm tall x 19 cm maximum thickness (truncated cylinder)	35 cm	North	3	1.1 m to floor
			South		1.8 m to south wall
252Cf 3745A (Cf 1)	two 30 cm x 30 cm (frontface) x 15 cm thick	35 cm	Northwest	6	1.5 m to floor
			Southwest		2.4 m to north wall 2.5 m to south wall 3.1 m to west wall
		50 cm	West	6	
		1 m	Northwest Southwest	4	
		1.5 m	Northwest Southwest	4	
252Cf 318 Bldg. (Cf 3)	two 30 cm x 30 cm x 15 cm water filled	35 cm	23°N of East 23°S of East	5	4.1 m to floor 4.9 m to ceiling 4.5 m to north wall 5.5 m to south wall
		50 cm	East	5	8.3 m to east wall 8.1 m to west wall
	one				

TABLE 11. TEPC Measurements

Source	Date of Measurement	Position	Dose Equivalent Rate, mrem/hr	Comments
PuF ₄ 3745A Bldg.	12/80	35-cm E	38.3	
		45-cm E	24.1	
		75-cm E	9.04	
		100-cm E	5.52	
		45-cm E	24.7	source rotated 90°
		45-cm E	24.6	source rotated 180°
		45-cm E	24.1	source rotated 270°
252Cf 3745A Bldg.	5/12/81	35-cm NW	2062	Phantom in SW
		35-cm SW	2207	Phantom in NW
		50-cm W	1050	
	11/14/80	1-m NW	351	
		1-m SW	348	
		1.5-m NW	178	
		1.5-m SW	182	
252Cf 318 Bldg.	9/15/80	50.5 cm	83.7	
		101.5 cm	22.4	
		149.0 cm	9.78	
		202.6 cm	7.49	
		50 cm	89.5	Phantom
		106 cm	20.8	behind
		119.5 cm	16.7	TEPC
		151 cm	11.1	
		200 cm	7.3	
	7/5/81	50.6 cm	67.5	
		60.5 cm	47.3	
		75.4 cm	31.9	
		90.4 cm	21.6	
		100.3 cm	18.2	
		110.3 cm	15.2	
		125.3 cm	11.9	
		135.2 cm	10.3	
		150.2 cm	8.8	

the TEPC for the 318 ^{252}Cf source. The differences in dose-equivalent rates are not significant. The dose rates decline slower than predicted by the inverse-square law for both ^{252}Cf sources, with the deviation being greater for the 3745A source.

NBS TRACEABILITY

The ^{252}Cf source in the 318 building was calibrated at NBS in terms of emission rate. For the conversion to dose-equivalent rates, we used the suggested conversion factor in ANSI N13.11 (ANSI 1978) ($3.4 \times 10^{-8} \text{ rem cm}^2$) and the inverse-square law. This procedure adequately describes the free-field neutron dose equivalent. The neutrons scattered from the source-mounting apparatus, the air, and the room surfaces add a scatter factor that is unique to each facility. The response of the Hanford dosimeter to the scattered neutrons in the 318 facility have been calculated and/or measured (see Section 2.0). The response can be corrected by dividing by 1.06. The TEPC measurements in the 318 facility show that the effects of scatter are much greater for the dosimeter than for the TEPC.

RESULTS FOR HAND-LOADED DOSIMETERS

Measurements were taken using dosimeters with removable TLD's. Two TLD's were packed in each location. The TLD's were tightly screened and carefully read and annealed outside of the dosimeter. Exposures were made using the calibration geometry for the PuF_4 source, the 1-m and 1.5-m geometries for the 3745A ^{252}Cf source and the 50-cm geometry for the 318 ^{252}Cf source. The exposure dates, geometries, average TLD readings and dosimeter response functions are given in Table 12. The errors on the response functions are based on estimates of variance for the TLD readings.

RESULTS FOR ROUTINE-PROCESSED DOSIMETERS

Dosimeters taken from the Hanford dosimeter pool were exposed to the fast-neutron sources and evaluated along with the routine-processed dosimeters. Because of the routine processing, comparing the fast-neutron responses for

TABLE 12. Results For Hand-Loaded Dosimeters

Source	Date	Location	Number of Dosimeters	TLD Readings, nC ^(a)			C5, rem/nC ^(b)
				R2	R3	R4	
PuF ₄	12/80		6	86.1	654	586	2.4 ₋ 0.14
			6	86.6	673	581	
			6	86.6	647	577	
	2/81		6	93.9	671	586	<u>2.47+0.24</u> 2.42 ₋ 0.12
				average			
				TLD Readings, nC ^(c)			
²⁵² Cf 3745A Bldg.	11/80	1 m NW	5	32.2	584	477	3.19 ₋ 0.18
		1 m SW	5	32.5	608	476	
	12/80	1 m NW	5	33.3	607	489	
		1 m SW	5	33.1	602	475	
	11/80	1.5 m NW	5	30.8	734	540	2.93 ₋ 0.18
		1.5 m SW	5	30.1	720	540	
	12/80	1.5 m NW	5	33.0	767	575	
		1.5 m SW	5	32.3	750	610	
				TLD Readings, nC ^(d)			
²⁵² Cf	2/81	50 cm	10	26.7	321	281	5.05 ₋ 0.15 ^(e)
318 Bldg.	3/81	50 cm	10	25.3	323	281	

(a) Adjusted to 1 rem field dose equivalent, for TEPC dose equivalent multiply by 1.28.

(b) K5 and K6 were calculated using Chip 2 readings. K5 = 1.12, K6 = 0.92. Errors are estimated from the fluctuations in the TLD readings.

(c) Adjusted to 1 rem TEPC dose equivalent.

(d) Adjusted to 1 rem NBS-traceable free-field dose equivalent.

(e) The dosimeter response function has been divided by 1.06 to account for the increased response due to scattered neutrons.

these dosimeters is more relevant to the effect of source changes on the Hanford dosimetry system. However, the interpretation of the data is more complex.

Routine dosimeters are read in batches according to fixed schedules. The reading of a batch is called a run, which lasts up to several weeks. Research dosimeters are typically read at the end of a run or in a slow period during a run.

Dosimeter readout variations are due to: 1) a variable reader efficiency (even during a run); 2) a different relative efficiency for each TLD position within the dosimeter (Reader No. 2); 3) TLD screenings with a standard deviation of 10-15%; and 4) a random TLD read error. The problem of differing relative efficiencies for the TLD positions (number 2 above) is small for neutron-only exposures if the calibrations providing K5 and K6 are done with those efficiencies. The fluctuations in the TLD readings for consecutively read dosimeters is dominated by the 10% to 15% screening variations.

The simplest method of source comparison was to expose a random set of pool dosimeters to the test situations of interest and have them read in one group using routine processing. The errors propagating to the final results were then due to TLD efficiency variations and random read errors. Table 13 contains such direct comparison data for the PuF_4 calibration geometry, the 35-cm and 50-cm ^{252}Cf geometries and the 35-cm ^{252}Cf geometry. The TLD readings are expressed in reader units (r.u.). The validity of the K5 and K6 values from the run calibration sets is assumed. The ^{252}Cf results have consistent C5 values.

Comparing ^{252}Cf exposures to the routine-run calibrations using PuF_4 is more complex. Two principal problems are: 1) the PuF_4 - and ^{252}Cf -exposed dosimeters are not read at the same time, and 2) the error in the determination of C5 from the PuF_4 -exposed dosimeters is large ($\sim 10\%$). In addition to the calibration dosimeters read before and after each run, there are generally twelve audit dosimeters per radiation type read interspersed throughout the run. The first problem can be reduced by using the audit-dosimeter results because they more closely represent the average reader normalization during the run and because they are drawn from the general dosimeter

TABLE 13. Results for Routine-Processed Dosimeters

(Direct Comparisons)

Source	Position	Dosimeters	Dose Equivalent, mrem	TLD Readings, r.u.			C5, rem/r.u. (a)
				R2	R3	R4	
PuF ₄	35-cm N,S ^(b)	12	1000 ^(c)	421	3551	3183	0.407 +0.029
	same	same	1280 ^(d)		same		0.520
²⁵² Cf 3745A	35-cm NW	12	966 ^(e)	165	2521	2123	0.596 +0.042
	35-cm SW	12	1034 ^(e)	168	2652	2226	0.608 +0.051
	50-cm W	12	1000 ^(e)	178	2828	2328	0.579 +0.058
²⁵² Cf 318 Bldg.	35-cm NE,SE	12	773 ^(f)	103	1363	1092	1.06+0.13

(a) K5 = 0.857, K6 = 0.970 were obtained from the April Monthly run. Errors are estimated from the fluctuations in the readings

(b) PuF₄ calibration geometry

(c) Dose equivalent is based on the field calibration. The exposure time is 33.3

(d) Based on the TEPC measurement

(e) These dose equivalents are based on TEPC measurements. The 35 cm 3745A Cf positions average to 1000 mrem

(f) NBS-traceable free-field dose. The dosimeter response has been corrected for neutron scatter.

pool. The uncertainties can be further reduced by using the (relatively well determined) C1 values from the ^{137}Cs calibration to help determine the reader normalization for each run. Table 14 contains the original and normalized C values for a six-month period. Fluctuations in the C1 values are dominated by normalization differences. Fluctuations in the original C5 values are due to both the normalization differences and the TLD efficiency errors. Use of the normalized values retain the normalization fluctuations, while reducing the errors due to TLD efficiency fluctuations. The estimated uncertainty in the normalized C5 values is 5%.

TABLE 14. Normalized C5 Values(a)

Run	Original Values		Normalized C5, rem/r.u.
	C1, rem/r.u.	C5, rem/r.u.	
OctM	0.478	0.652	0.632
NovM	0.467	0.666	0.618
DecM	0.508	0.613	0.672
DecQ	0.539	0.829	0.714
DecA	0.435	0.613	0.576
DecCU	0.458	0.515	0.606
JanM	0.491	0.557	0.650
FebM	0.451	0.606	0.597
MarchM	0.546	0.673	0.723
MarchQ	0.506	0.738	0.670
Average	0.488	0.646	
% SD per run	8%	14%	

$$\text{Normalized C5} = (\text{average C5}) \left(\frac{\text{C1}}{\text{average C1}} \right)$$

(a) All values obtained from audit dosimeter results.

The dosimeter data is presented in Table 15. A group of 50 dosimeters was taken from the Hanford dosimeter pool and cycled for several measurements. The dosimeters exposed in each position, the dose delivered, the readings, and the calculated C5 values are given. The 3745A ^{252}Cf values are greater for the December monthly run than for the December clean-up run, which agrees with the difference in normalization shown in the PuF_4 calibrations. Also, the ratio of R3 to R4 changes between runs. This is approximately compensated for by the difference in the K5 values. Thus, even though both the overall normalization and the relative read efficiency between positions changes between runs, they are approximately compensated for by using each run's calibration factors.

The dominant error in each C5 determination is due to the TLD screening. An unbiased estimate can be attained only if the dosimeters are chosen at random and are representative of the general pool. However, because the same dosimeters were used for both of the 3745A ^{252}Cf runs, the C5 determinations are not independent; they have the same TLD efficiency biases. We have obtained relative TLD efficiencies using a ^{137}Cs exposure. This is equivalent to calibrating the relative response of the dosimeters. The relative TLD efficiencies for ^{137}Cs exposures versus fast-neutron exposures was checked with no apparent effect found. Table 16 contains the same data as in Table 15, but with the TLD efficiencies taken out. The data is normalized to the average efficiency of all 50 dosimeters. Shifts in the C5 factors of greater than 10% were observed. These results are less biased even though the same normalizations were used for all runs.

COMPARISON OF RESULTS

The C5 values used to calculate the ^{252}Cf -to- PuF_4 ratios for the 3745A facility are presented in Table 17. The ^{252}Cf -to- PuF_4 ratios for the routine-processed dosimeters are consistent for all geometries. The results for the hand-loaded dosimeters are lower, but the difference is not statistically significant. The data indicates that the relative response of the Hanford dosimeter and the TEPC are approximately the same for the 3745A facility. This is attributed to both sources creating similar scattered-neutron spectra

TABLE 15. Results for Routine-Processed Dosimeters

(Indirect Comparisons)

^{252}Cf 3745A Building							
UST Run	Dosimeter Numbers	Location	Dose Equivalent, mrem	TLD Readings, r.u.			C5 rem/r.u.
				R2	R3	R4	
December ^(a) Monthly	22-25, 30-33	1 m NW	994.9 ^(b)	126	2948	1859	
	26-29, 34-37	1 m SW	994.9 ^(b)	140	2875	1873	1.05
	38-41	1.5 m NW	647.2 ^(b)	82	2367	1311	0.90
	42-45	1.5 m SW	647.2 ^(b)	83	2550	1720	
December ^(c) Clean-Up	22-25, 30-33	1 m NW	986.4 ^(b)	141	2520	1774	0.95
	26-29, 34-37	1 m SW	986.4 ^(b)	151	2563	1886	
	38-41	1.5 m NW	641.6 ^(b)	73	1937	1308	0.82
	42-45	1.5 m SW	641.6 ^(b)	84	2175	1558	
^{252}Cf 318 Building							
February ^(d) Monthly	1-10	50 cm	100 ^(e)	17.3	165.1	139.3	1.07

(a) K5 = 0.768, K6 = 0.871, normalized PuF_4 C5 = 0.672.

(b) Based on TEPC measurements.

(c) K5 = 0.933, K6 = 0.938, normalized PuF_4 C5 = 0.606.(d) K5 = 0.895, K6 = 0.954, normalized PuF_4 C5 = 0.597.

(e) NBS-traceable free-field dose. The dosimeter response has been corrected for neutron scatter.

in the same irradiation environment. The dosimeter responses to both sources have been calculated relative to the TEPC measurements. To obtain the ratio to the field-based calibration for one of the ^{252}Cf irradiation geometries multiply the Table 17 value by 1.28.

Table 18 contains the response ratio for the 318 ^{252}Cf source compared to the PuF_4 source. The 50-cm position shows about a 60% greater response to the PuF_4 source than the ^{252}Cf source. The dramatically increased response of the dosimeter to lower-energy neutrons is well documented (Endres, et al. 1981). The major portion of the increased response is probably due to

TABLE 16. Results for Routine-Processed Dosimeters

(Indirect Comparisons, Data Smoothed)

²⁵² Cf 3745A Building		Location	Dose Equivalent, mrem	Smoothed Readings, r.u.			C5 rem/r.u.
UST Run	Dosimeter Numbers			R2	R3	R4	
December ^(a) Monthly	22-37	1 m	994.9 ^(b)	146	2957	1962	0.93 +0.08
	38-45	1.5 m	647.2 ^(b)	94	2491	1510	-0.96 +0.14
December ^(c) Cleanup	22-37	1 m	986.4 ^(b)	156	2575	1917	0.85 +0.07
	38-45	1.5 m	641.6 ^(b)	86	2058	1477	-0.75 +0.11
²⁵² Cf 318 Building							
February ^(d) Monthly	1-10	50 cm	100 ^(e)	17.0	165.7	133.7	1.20 +0.13

(a) K5 = 0.768, K6 = 0.871, normalized PuF₄ C5 = 0.672.

(b) Based on TEPC measurements.

(c) K5 = 0.933, K6 = 0.938, normalized PuF₄ C5 = 0.606.(d) K5 = 0.895, K6 = 0.954, normalized PuF₄ C5 = 0.597.

(e) NBS-traceable free-field dose. The dosimeter response has been corrected for neutron scatter.

the increased level of scattered neutrons in the 3745A facility. The response of the TEPC is also affected by scattered neutrons, but to a much smaller level. Comparing the two facilities using TEPC calibrations for both sources, the dosimeter-response difference is reduced to about 45%.

The 318 ²⁵²Cf source provides a comparison between the field-based calibration and an NBS-traceable calibration. The two calibrations are compared in Table 19. The results for the hand-loaded and routine-processed dosimeters are consistent and show a factor of two differences between calibrations. The dosimeter response is greater for the field calibration. The difference between the calibrations does not imply that one is in error.

TABLE 17. The Hanford-Dosimeter Response to the 3745A ^{252}Cf Source Relative to the 3745A PuF_4 Source^(a)

Geometry	Run	Routine-Processed Dosimeters			Hand-Loaded Dosimeters		
		PuF_4 C5, rem/r.u.	Cf C5, rem/r.u.	Ratio	PuF_4 C5, rem/nC	Cf C5, rem/nC	Ratio
35-cm NW,SW	AprM	0.520	0.602	1.16 ± 0.09			
50-cm W	AprM	0.520	0.579	1.11 ± 0.14			
1-m NW,SW	DecM	0.859	0.93	1.09 ± 0.08	3.10	3.19	1.03 ± 0.08
	DecCU	0.774	0.85				
1.5-m NW,SW	DecM	0.859	0.96	1.04 ± 0.14	3.10	2.93	0.95 ± 0.07
	DecCU	0.774	0.75				

(a) The C5 values are calculated using TEPC measurements.

TABLE 18. The Hanford-Dosimeter Response to the 318 ^{252}Cf Source Relative to the PuF_4 Source^(a)

Geometry	Run	Routine-Processed Dosimeters			Hand-Loaded Dosimeters		
		PuF_4 C5, rem/r.u.	^{252}Cf C5, rem/r.u.	Ratio	PuF_4 C5, rem/nC	^{252}Cf C5, rem/nC	Ratio
35-cm NE,SE	AprM	0.520	1.06	2.04 ± 0.30			
50-cm E	FebM	0.763	1.20	1.57 ± 0.21	3.10	5.05	1.63 ± 0.10

(a) The PuF_4 C5 values are calculated using TEPC measurements.

TABLE 19. Comparison of the Historical Field Calibration
to an NBS-Traceable ^{252}Cf Calibration

	C5	
	Hand-Loaded Dosimeters, rem/nC	Routine- Processed Dosimeters, rem/r.u.
Field Dose Equivalent (PuF ₄)	2.42 $\pm$ 0.12	0.597 $\pm$ 0.028
NBS-Traceable Dose Equivalent (^{252}Cf in 318)	5.05 $\pm$ 0.15	1.20 $\pm$ 0.13
Ratio	2.09 $\pm$ 0.12	2.01 $\pm$ 0.24

The dosimeter responds differently to neutron spectra of differing composition. The spectra in a work environment is more likely to contain a significant amount of low-energy neutrons because of shielding material and confined spaces. A valid procedure to establish traceability for the fast-neutron calibration is to relate the current field-measured neutron response for the dosimeter to its response to the NBS-traceable source.

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