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P. L. Roberson
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April 1983

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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FACILITIES AND PROCEDURES USED FOR THE PERFORMANCE TESTING OF DOE PERSONNEL DOSIMETRY SYSTEMS

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Allentown, Pennsylvania

PREFACE

This work is part of the research project "Technical Guidelines for Personnel Dosimetry Calibrations" performed by the Pacific Northwest Laboratory for the Office of Nuclear Safety, Office of Environmental Protection, Safety and Emergency Preparedness, Department of Energy (DOE). The scope of the project is to develop guidelines for radiological calibrations of personnel dosimeters and radiation protection instruments used at DOE facilities. A data base was developed on the performance of DOE personnel dosimetry systems through a voluntary testing program. This report contains the test methodologies that were employed.

SUMMARY

Radiological calibration facilities for personnel dosimeter testing were developed at the Pacific Northwest Laboratory (PNL) for the Department of Energy (DOE) to provide a capability for evaluating the performance of DOE personnel dosimetry systems. This report includes the testing methodology used for the collection of data described in Performance Comparisons of Selected Personnel Dosimeters in Use at Department of Energy Facilities (Roberson, et al. 1983). Part of the dosimeter testing program followed procedures outlined in the draft standard ANSI N13.11, "Criteria for Testing Personnel Dosimetry Performance" (ANSI 1978, 1982). The information presented here meets requirements specified in draft ANSI N13.11 for the testing laboratory.

The capabilities of these facilities include sealed source irradiations for ^{137}Cs, several beta-particle emitters, ^{252}Cf, and machine-generated x-ray beams. The x-ray beam capabilities include filtered techniques maintained by the National Bureau of Standards (NBS) and K-fluorescent techniques. The calibration techniques, dosimeter irradiation procedures, and dose-equivalent calculation methods follow techniques specified by draft ANSI N13.11 where appropriate.

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1.0 INTRODUCTION

The Pacific Northwest Laboratory (PNL) was commissioned by the Department of Energy (DOE) to develop a data base for evaluating the calibration, design, and performance of DOE personnel dosimetry systems and to prepare a technical document to provide guidance to DOE and DOE contractors in personnel dosimetry calibration procedures. The calibration facilities described here were developed to provide testing of the personnel dosimeters. Eleven major DOE laboratories participated in the performance testing. Results are reported in Performance Comparisons of Selected Personnel Dosimeters in Use at Department of Energy Facilities (Roberson, et al. 1983).

The performance tests were based on those described in draft ANSI N13.11, "Criteria for Testing Personnel Dosimetry Performance" (ANSI 1978, 1982). The information about the test conditions required by the draft standard is included in this report. Because the standard was undergoing revisions while the performance testing was underway, the tests performed were not those described in the most recent version (ANSI 1982). Revisions in some of the test methods and in the test analysis techniques were made to accommodate changes in the draft standard where possible.

The tests performed are listed in Table 1. The tests listed under the draft ANSI N13.11 were based on the radiation protection categories listed in the standard. Additional tests were performed to provide an improved understanding of dosimeter energy and radiation mixture dependences and were designed in a manner consistent with the draft ANSI N13.11 tests.

TABLE 1. Irradiation Categories

Test Category - ANSI N13.11[a]	Source(s)
High-Energy Photons	^{137}Cs
Low-Energy Photons	NBS Filtered X-Ray Techniques MFC, MFG, MFI[b]
Beta Particles	$^{90}Sr/^{90}Y$
Photon Mixtures	^{137}Cs Plus Filtered X-Ray Techniques
Photon/Beta Mixtures	^{137}Cs Plus $^{90}Sr/^{90}Y$
Neutron	^{252}Cf (unmoderated)
Additional Test Categories	
Photon Energy Response Function	K-Fluorescent X Rays (16 keV, 58 keV)
	Heavily Filtered Techniques (HFI)
Beta Energy Response	^{85}Kr
Neutron/X-ray Mixture	^{252}Cf Plus 58 keV K-Fluorescent X Rays
Neutron Energy Response	Heavy Water Moderated ^{252}Cf

(a) The July 1978 version was used for the data collection.
(b) See NBS SP 250 Appendix (NBS 1981).

2.0 IRRADIATION FACILITIES

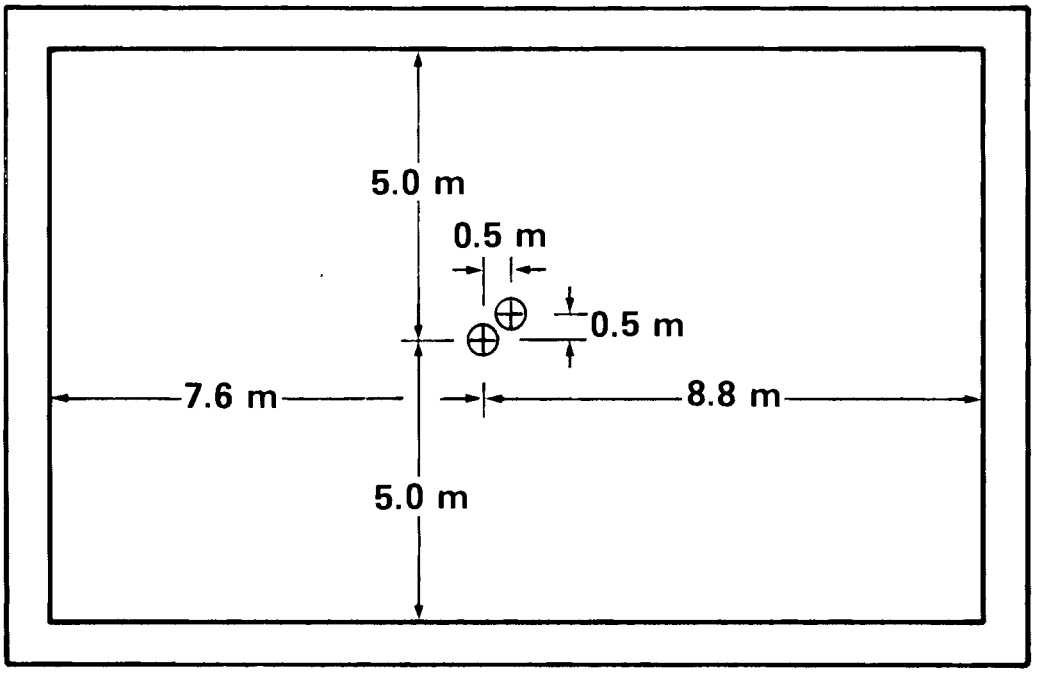
The irradiation facilities are housed in a renovated experimental reactor building. The upper containment room was used as a low-scatter environment for ^{252}Cf and ^{137}Cs irradiations. The lower containment and adjacent areas were used for beta-source irradiations and x-ray irradiations.

2.1 LOW-SCATTER ROOM (^{137}Cs and ^{252}Cf)

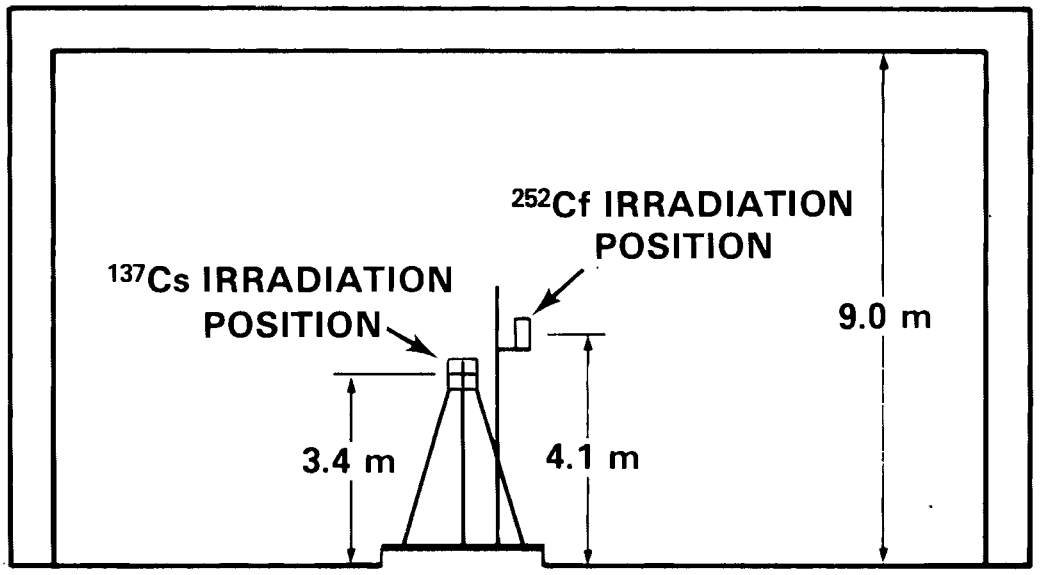
A relatively large room is desirable for neutron irradiations because of the large amount of secondary scattering from room surfaces (Schwartz and Eisenhauer 1982). The room dimensions for the low-scatter facility are shown in Figure 1. The source positions were in the approximate center of the room. The minimum distance to a room surface was 3.4 m for the ^{137}Cs source and 4.1 m for the ^{252}Cf source. All room surfaces are concrete.

The source-positioning mechanisms are shown in Figure 2. The ^{137}Cs source was pneumatically pulled into a collimator assembly from a storage position in the floor. The ^{137}Cs beam was collimated by a lead enclosure (see Figure 3) with wall thicknesses of 5 cm on the sides and 6 cm on the top and bottom. An opening 22.3 cm wide by 10 cm high allowed a uniform field at the face of the phantom. A 2-Ci source was encapsulated in an aluminum cylinder, approximately 1.9 cm long by 1.3 cm in diameter. Dosimeters were irradiated on a 30-cm x 30-cm x 15-cm methylmethacrylate (plexiglas) phantom. The distance between the source center and the front face of the phantom was one meter.

The ^{252}Cf source was pulled into position using a cord-and-pulley system and was stored inside a paraffin-filled drum. The source was moved up (irradiation position) or down (storage position) inside of a stainless-steel tube. A pin installed at the top of the tube stopped the source assembly, providing a reproducible irradiation position. The irradiation geometry for the ^{252}Cf source is shown in Figure 4. The source was pulled into the irradiation position at a height corresponding to the center of the phantom.



(a) Top View



(b) Side View

FIGURE 1. Low-Scatter Room

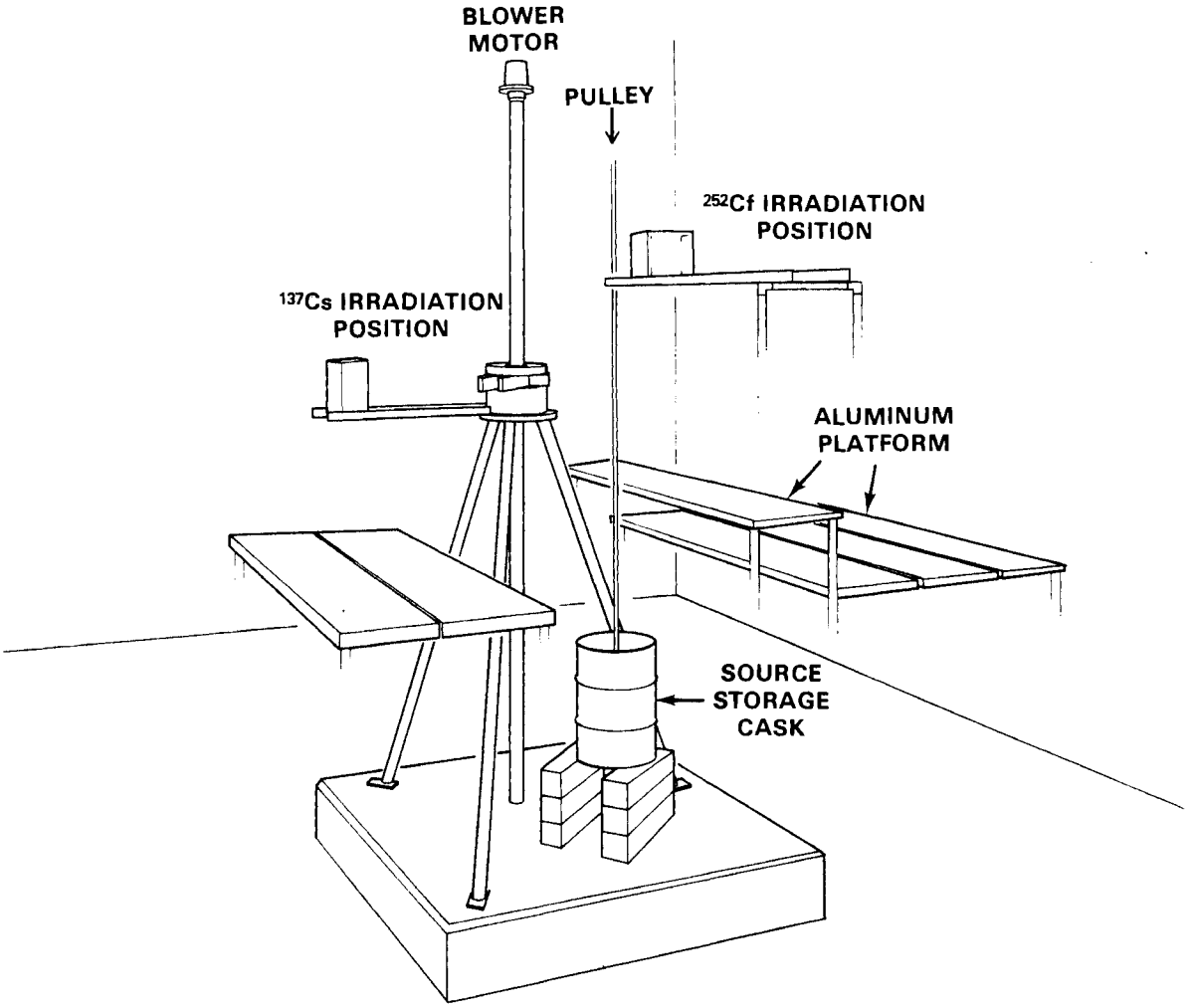


FIGURE 2. ^{137}Cs and ^{252}Cf Irradiation Equipment

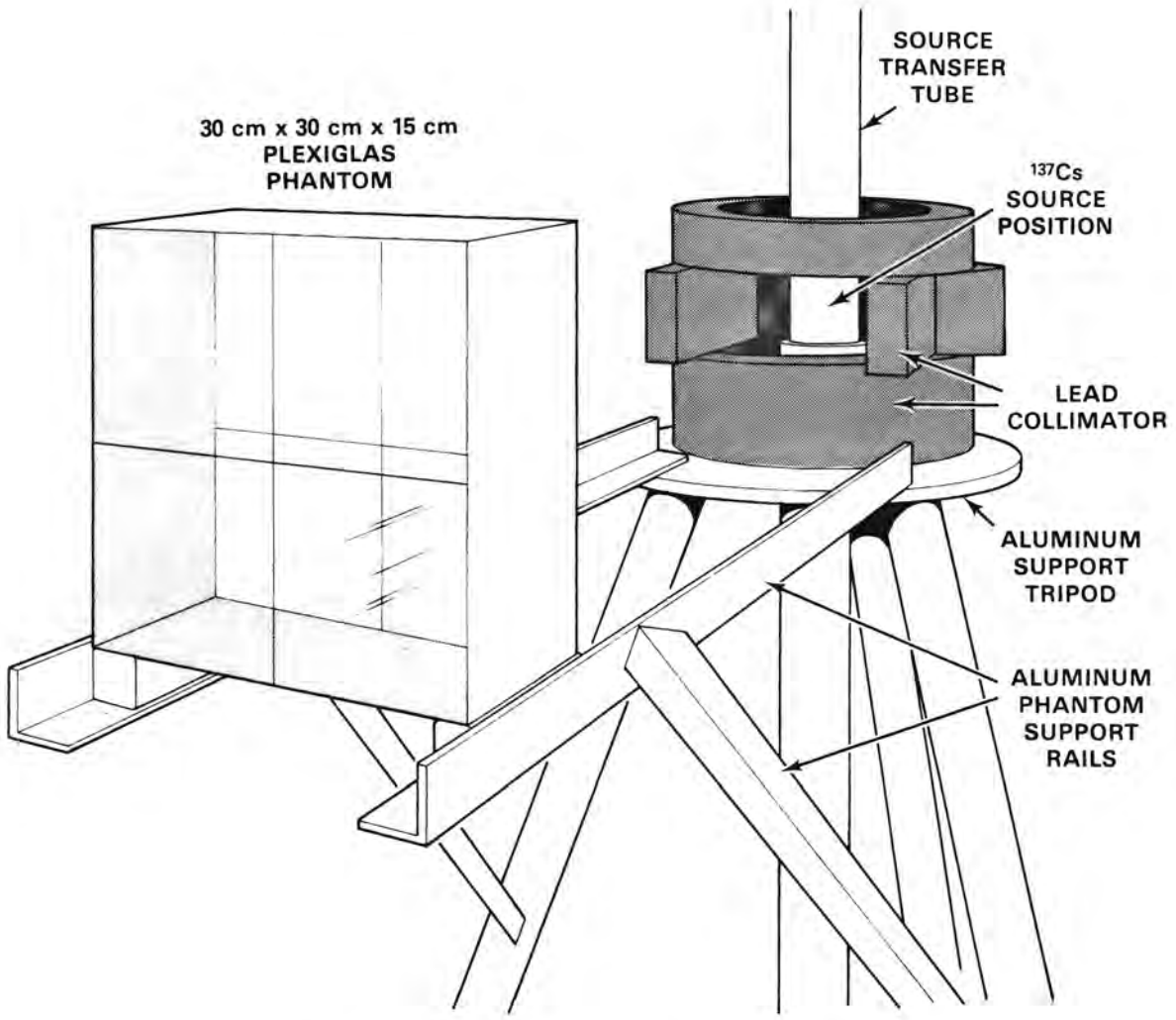


FIGURE 3. ^{137}Cs Irradiation Geometry

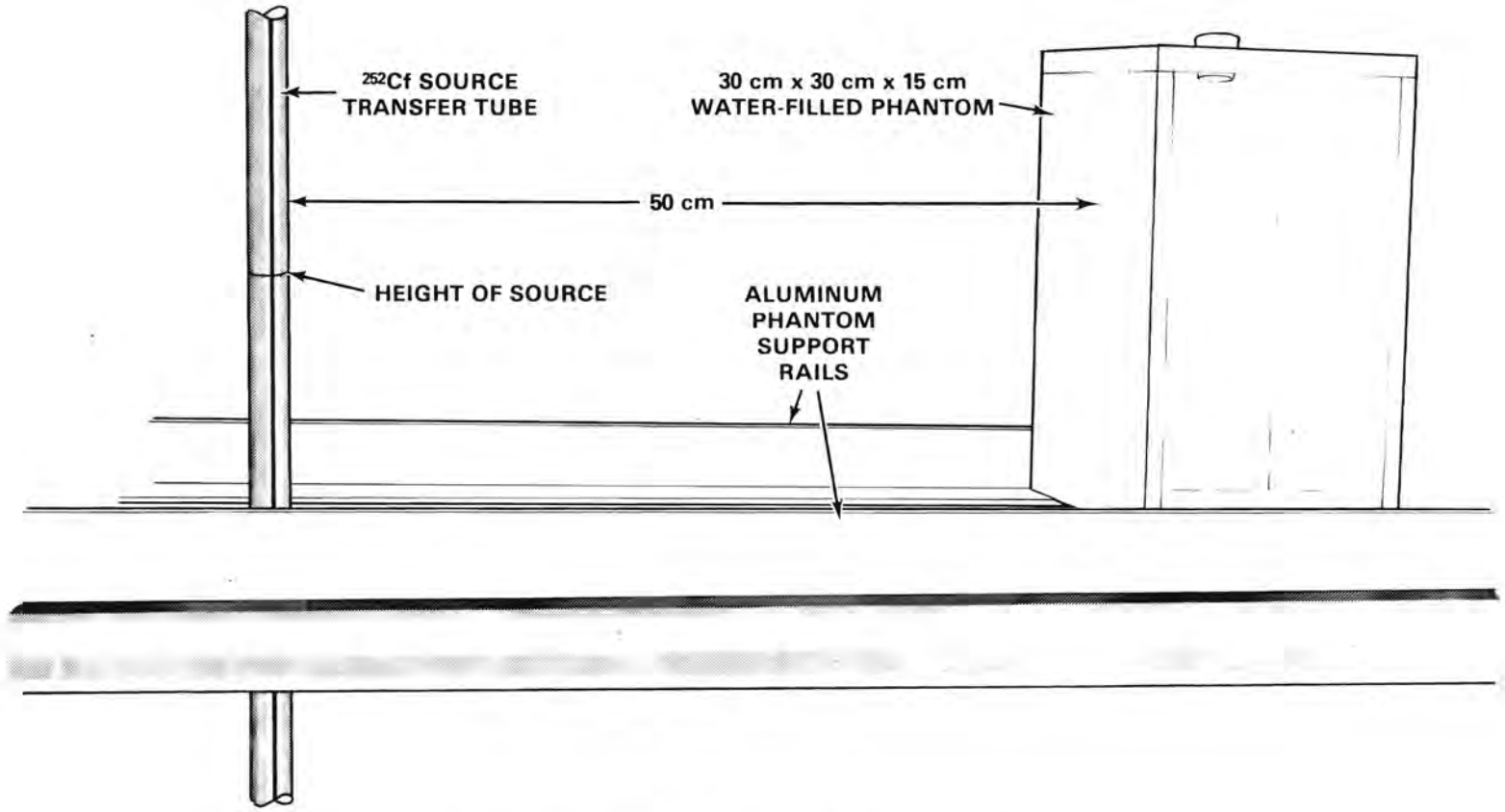


FIGURE 4. ^{252}Cf Irradiation Geometry

The dosimeters were irradiated on the front face of a 30-cm x 30-cm x 15-cm water-filled phantom.[a] The distance between the source center and the front face of the phantom was 50 cm. The mass of the ^{252}Cf source was 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. Although aluminum scaffolding was used to provide platforms for mounting dosimeters and equipment, it did not contribute a measurable amount of scattered radiation to either the ^{137}Cs or the ^{252}Cf exposures.

2.2 BETA IRRADIATION ROOM

Beta-source exposures were made using the exposure apparatus shown in Figure 5. Sources were mounted on top of a remotely controlled antenna. The source was either moved up into the irradiation position or retracted into the storage box. A spherical ^{90}Sr-^{90}Y source was used with two 15-cm x 15-cm x 0.0076-cm aluminum filters (21 mg/cm^2 each) and two 30-cm x 30-cm x 15-cm methylmethacrylate (plexiglas) phantoms. The filters were mounted approximately 10 cm from the source. The plexiglas phantoms were supported by two aluminum frames, with the center of each phantom 50 cm above the table. For the dosimeter irradiations, the front face of each phantom was placed 50.5 cm from the center of the sphere. The distance from the source to the floor was 1.4 m, and the distance to the nearest wall was 3.3 m.

The ^{90}Sr beta source had an activity of 40 mCi. A thin (<0.04 cm) layer of ^{90}Sr was spread uniformly over the surface of a vi-cor (quartz) sphere. A covering of colloidal graphite, approximately 0.035 cm thick (~80 mg/cm^2), preserved the integrity of the source. The sphere had a diameter of approximately 2.5 cm. The thickness of the source encapsulation plus the aluminum filtration was approximately 100 mg/cm^2.

(a) The latest version of ANSI N13.11 (ANSI 1982) specifies a 40 cm x 40 cm x 15 cm phantom of methylmethacrylate for neutron irradiations.

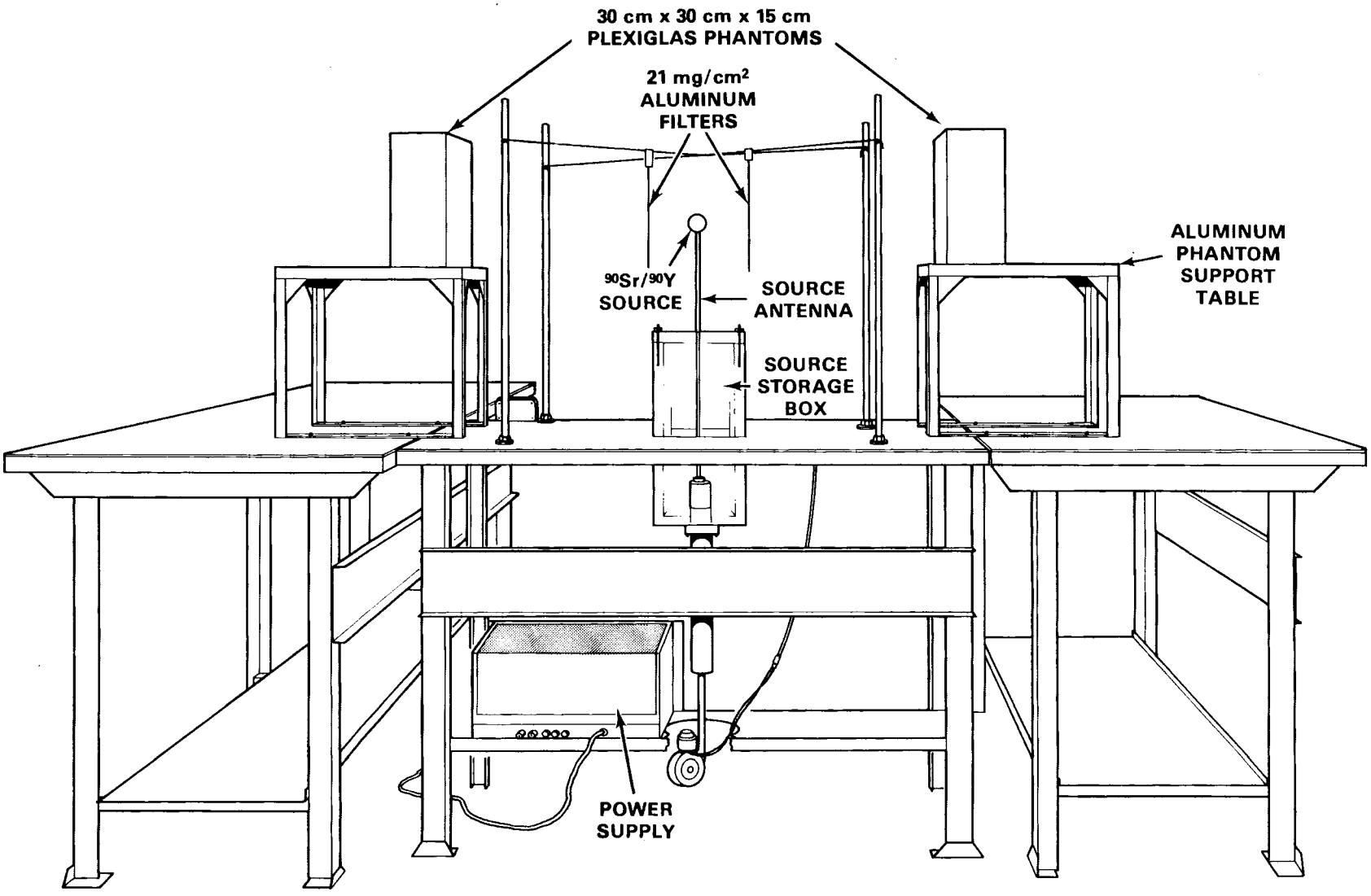


FIGURE 5. Beta Irradiation Apparatus

2.3 X-RAY FACILITY

The two x-ray generators used to provide lightly filtered (L), medium-filtered (MF), and heavily filtered (HF) NBS techniques and K-fluorescent x rays are shown in Figure 6. A 320 kVp Gemini tube, manufactured by Picker Industrial, was used for the MF, HF, and K-fluorescent techniques. A 160 kVp tube manufactured by Philips was used for lightly filtered x rays. For the NBS techniques, the beams were directed horizontally through filters, collimators and a transmission ionization chamber. K-fluorescent x rays were generated by directing the primary beam downward on a target that was mounted at 45° relative to the beam axis (Kathren, Rising and Larson 1971). However, this arrangement is not shown in Figure 6. The characteristic x rays from the target were collimated in the horizontal direction. The source-to-phantom distances for dosimeter irradiations were 1 m for NBS techniques and 50 cm for K-fluorescent techniques.

The x-ray machine is located in a corner of a long room (see diagram of room in Figure 7). Lead-lined partitions separate the x-ray room from the control room and hallway. All other nearby walls are concrete or cinder block. The ceiling is sufficiently high so that it did not provide a significant contribution to the scatter.

The transmission ionization chamber was used to monitor the output of the x-ray machines. Given exposures were reported based on the chamber readings. The chamber output was measured using a calibrated electrometer. Temperature and pressure corrections to the chamber readings were made automatically by the process-control computer. X-ray room conditions were continuously monitored using temperature- and pressure-measuring instruments interfaced with the computer.

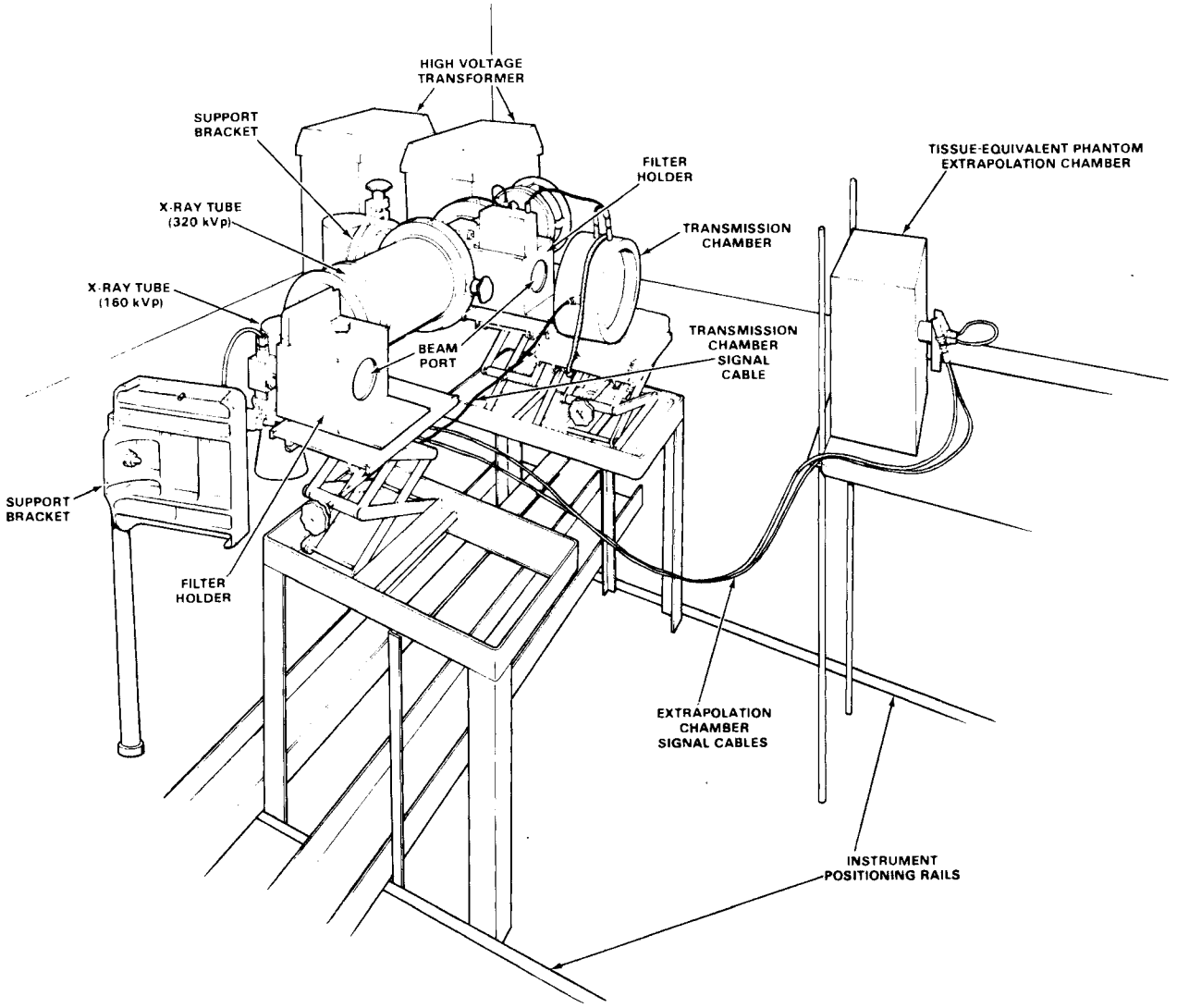


FIGURE 6. X-Ray Equipment

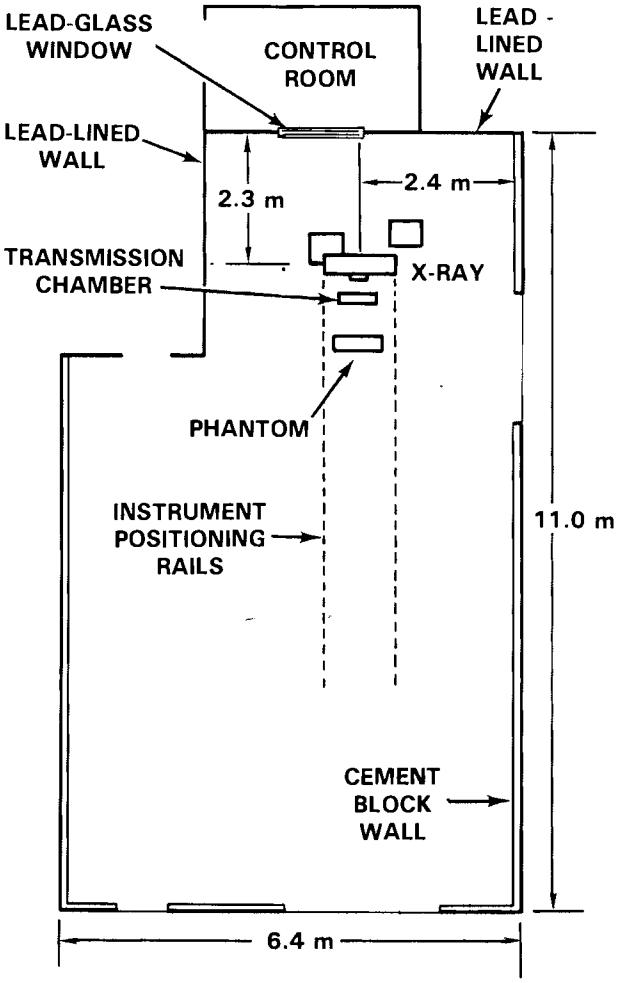


FIGURE 7. Plan View of the X-Ray Room

3.0 CALIBRATION TECHNIQUES

Instrument traceability[a] to the NBS was maintained according to the type of radiation. The paths of traceability are:

- use of an NBS-calibrated ionization chamber as a transfer standard for exposure measurements for specific photon beams;
- use of a free-air ionization chamber (FAIC) as a primary standard for x-ray exposure calibrations not offered by NBS;
- direct calibration by NBS of dose rate for a beta source;
- use of a tissue-equivalent extrapolation chamber as a transfer instrument for absorbed dose measurements between an NBS-calibrated beta source and beta sources used for routine irradiations;
- direct calibration by NBS of neutron-source emission rates.

The calibration methods for photon, beta and neutron sources are described in this section. Table 2 contains a summary of the calibration and irradiation techniques.

3.1 PHOTON CALIBRATIONS

Photon calibrations were performed for ^{137}Cs, NBS x-ray techniques and K-fluorescent x-ray techniques. For the ^{137}Cs and NBS techniques, Victoreen transfer standards, Models 415, 415A and 415B, were used to relate NBS calibrations to PNL calibrations. Victoreen FAICs, Models 480 and 481, were used to calibrate the K-fluorescent x-ray techniques. The FAIC results were intercompared with the transfer standards to assure reliability of operation.

The ionization chambers were used to measure exposure rates in air at fixed calibration points. The ^{137}Cs and NBS filtered x-ray beams were calibrated at a source-to-detector-center distance of one meter. K-fluorescent x-ray beams were calibrated at 50 cm. The electrometers used with the chambers were calibrated using a Keithley Model 261 picoampere source, which is recalibrated annually by the Hanford Engineering Development Laboratory.

(a) For a discussion on traceability, see Eisenhower (1982).

TABLE 2. Calibration and Irradiation Techniques Used for Dosimeter Performance Testing

Source	Calibration Method	Rem Conversion Factor	Irradiation Geometry
^{137}Cs	Exposure in Air	ANSI N13.11	On phantom[(a)] = 30 cm x 30 cm x 15 cm Source to detector = 1 m
X Ray	Exposure in Air	ANSI N13.11	On phantom[(a)] = 30 cm x 30 cm x 15 cm Source to detector = 1 m (filtered techniques) 50 cm (K-fluorescent techniques)
Beta	Absorbed Dose at 7 mg/cm^2	1.00	On phantom[(a)] = 30 cm x 30 cm x 15 cm Source to detector = 50.5 cm ($^{90}Sr/^{90}Y$) 50 cm (^{85}Kr) Filtration = 100 mg/cm^2 ($^{90}Sr/^{90}Y$)
^{252}Cf	Emission Rate	ANSI N13.11 plus scatter corrections	On phantom = 30 cm x 30 cm x 15 cm Water-filled plastic box Source to surface = 50 cm Room size = 10 m x 17 m x 9 m Source position = approximately centered in room

(a) Methylmethacrylate.

The x-ray irradiations were monitored by a transmission ionization chamber (see Figure 6) that was calibrated using a transfer standard or FAIC for each x-ray technique. The exposure rate for the ^{137}Cs source was calibrated for a timed irradiation.

3.2 BETA CALIBRATIONS

Beta source calibrations were performed using a tissue-equivalent extrapolation chamber (TEEC) with a front window thickness of 7 mg/cm^2. The extrapolation chamber was calibrated using a $^{90}Sr/^{90}Y$ source that had been calibrated for dose rate by NBS. The NBS-calibrated source was encapsulated in aluminum with a front window thickness of 0.25 mm (70 mg/cm^2). The NBS calibration was performed at 35 cm using an extrapolation chamber with a front window thickness of 0.7 mg/cm^2. A thin window extrapolation chamber was used to relate the calibration to the 7 mg/cm^2 depth.

The NBS-based calibration was compared to that of the beta secondary standard manufactured by Buchler Gmbh and Co. and calibrated at the Physikalisch-Technische Bundesanstalt (PTB, the national bureau of standards for the Federal Republic of Germany). The discrepancy between calibrations was 5% (see Table 3). If a correction is made for the different stopping power ratios used, the discrepancy increases. Estimated uncertainties for the $^{90}Sr/^{90}Y$ calibrations

TABLE 3. Comparison of NBS and PTB Calibrations

Source	Filtration	Distance	Calibration	Ratio of[a] TEEC to Calibration
$^{90}Sr/^{90}Y$	70 mg/cm^2 Al	35 cm	NBS	1.07±0.02[b]
$^{90}Sr/^{90}Y$	50 mg/cm^2 Ag	30 cm, 50 cm	PTB	1.02±0.02[c]

(a) Both the extrapolation chamber measurement and the calibration are expressed in mrad/hr at 0.007 mg/cm.
(b) The NBS calibration used an air to water stopping power ratio of 1.15. A factor of 0.987 was applied to correct to tissue.
(c) The PTB calibration used an air to tissue stopping power ratio of 1.111.

were 5% and 2% for NBS and PTB, respectively. After a discussion with personnel at NBS concerning this discrepancy, they recommended that we use the PTB standards until NBS develops a comparable capability.

3.3 ^{252}Cf CALIBRATION

Traceability of the ^{252}Cf source was based on an NBS emission-rate calibration. A conversion factor of 3.4×10^{-8} rem-cm^2/n (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/n (Schwartz and Eisenhauer 1982). The ^{252}Cf source strength was corrected for decay according to a 2.65-year half life.

Corrections to the dosimeter readings for neutrons scattered in the exposure facility were calculated using tabulated values developed by NBS (Schwartz and Eisenhauer 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 to 1.3%.

The room-return correction for the albedo dosimeter was checked using the Hanford Multipurpose Dosimeter. Groups of six Hanford dosimeters were irradiated at distances of 50 cm, 70 cm, 100 cm, 140 cm, 170 cm, and 200 cm from the source. Each dosimeter contained tightly screened TLDs that were read manually. After background subtraction, dosimeter responses were corrected for source 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 and Eisenhauer 1982), giving a linear relationship between $D(r)r^2$ and r^2, where $D(r)$ is the dosimeter response at distance r. A linear least-squares fit to the data points was used to obtain the correction factor. The scatter correction in percent per square meter was obtained by dividing the slope by the intercept. The curve is shown in

Figure 8. The measured room return correction was 9%/m^2. Using this value the total scatter correction was 4.4%, 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 6% of the free-field neutron dose-equivalent rate. Measurements using TLDs behind 90 mg/cm^2 plastic, 180 mg/cm^2 aluminum plus 180 mg/cm^2 plastic, and 760 mg/cm^2 tin plus 150 mg/cm^2 plastic were 6.4%, 5.5%, and 5.1% of the free-field dose-equivalent rate, respectively.

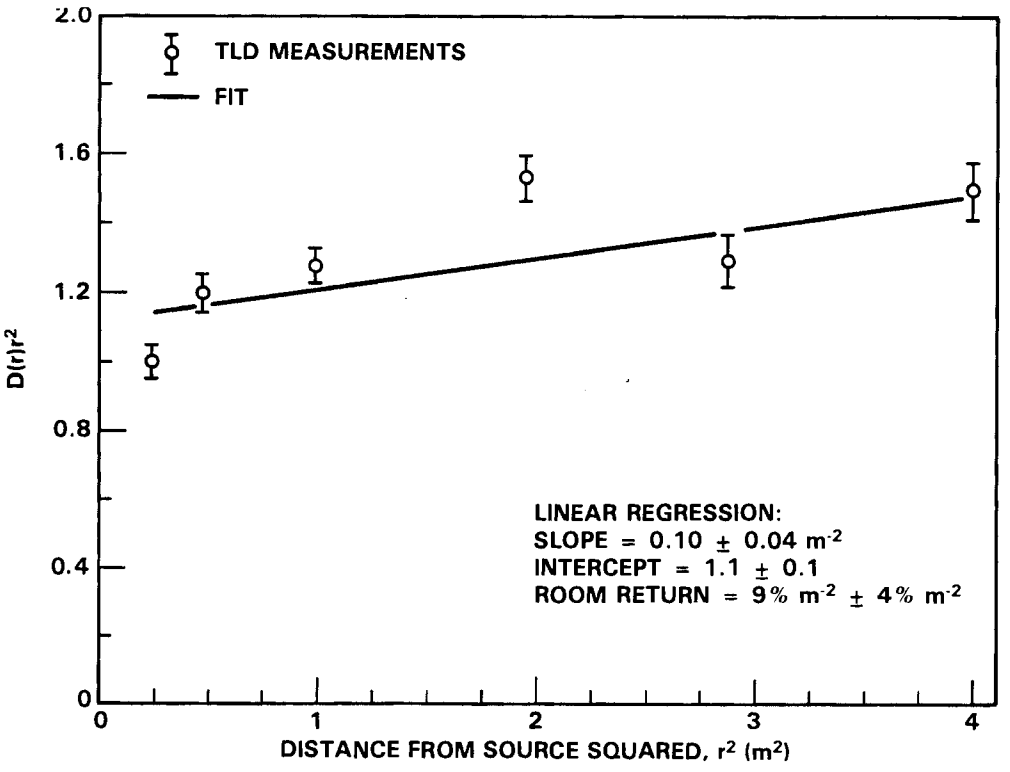


FIGURE 8. ^{252}Cf Room Return for the PNL Low-Scatter Facility Using the Hanford Multipurpose Dosimeter

4.0 DOSIMETER IRRADIATION PROCEDURES AND UNCERTAINTIES

Dosimeter irradiation procedures and maximum levels of uncertainty are specified for the tests described in draft ANSI N13.11. These guidelines were followed as closely as possible. Major differences between the irradiations performed and those specified were due to the changes in the drafts of the standard.

4.1 IRRADIATION PROCEDURES

Information on phantom types, sizes, and distances from the source center is contained in Table 2. The front face of the phantom was placed at the calibration point in all cases. Dosimeters without clips were taped flush to the phantom. Dosimeters with clips were clipped to a strip of tape such that the clip was in contact with the phantom.

The dosimeters were mounted such that the sensitive elements were within a 10-cm x 10-cm area centered on the phantom. The number of dosimeters irradiated simultaneously was dependent upon dosimeter size. All sealed-source irradiations were timed manually.

4.2 IRRADIATION UNCERTAINTIES

Draft ANSI N13.11 (ANSI 1982) specifies that the uncertainties in the assignment of the given dose equivalent be less than 5%, including uncertainties due to:

- source standardization
- NBS calibration
- use of transfer standard
- irradiation reproducibility
- timing or exposure monitoring
- dosimeter positioning (including beam nonuniformity)
- scattered radiation at the dosimeter site.

Not included in the total are uncertainties for the conversion factors used to compute the dose equivalent and for the assignment of the photon component of neutron irradiations. Uncertainties associated with each type of irradiation are discussed in the following sections. Table 4 contains a summary of the contributions to the total uncertainty for each source type.

TABLE 4. Irradiation Uncertainties

Source of Uncertainty	^{137}Cs, %	X Rays, %	$^{90}Sr/^{90}Y$, %	^{252}Cf, %
NBS calibration	2	2	5 (2)[a]	1.2
Use of transfer standard	1	1	2	-
Irradiation reproducibility	2	∿2	<2	N[b]
Timing or exposure monitoring	≤1	N	≤1	N
Dosimeter positioning (including beam nonuniformity)	2	∿2	1	2
Scattered radiation	N[c]	N	N	2
Statistical	3	3	3	2
Systematic	2	2	5 (2)[a]	3
Total	4	4	6 (4)[a]	4

(a) Based on the beta secondary standard calibrated at the PTB.
(b) N = negligible.
(c) The uncertainty in determining photon scatter is negligible for the deep dose only. The shallow dose (0.007 cm tissue depth) was measured to be approximately 5% greater than the deep dose (1 cm tissue depth). Draft ANSI N13.11 specifies the same exposure-to-dose conversion factor for both depths.

4.2.1 ^{137}Cs

The uncertainty in the ionization chamber transfer standard calibration relative to the definition of the Roentgen is estimated by NBS to be 2%. Uncertainties for the use of the calibrated ion chamber to measure exposures at the irradiation position were approximately 1%. Errors in source positioning

occurred due to differences in the position of the source within the source guide. Based on reproducibility measurements, the uncertainty for an irradiation was 2%. Exposure timing errors may have been as large as two seconds due to the source transit time in the tube. For a 30-mrem exposure (the lower limit specified in draft ANSI N13.11), the timing error was, at most, 1%.

Errors due to phantom positioning were small. A more significant error was due to the beam nonuniformity. The variation of beam intensity over the central 10-cm x 10-cm region used for dosimeter irradiations was approximately ±2% with respect to the center calibration point, as measured using an ionization chamber with and without phantom backing.

The contribution to the uncertainty due to scattered radiation for the given deep dose is negligible because 1 cm is beyond the depth required for electronic equilibrium (i.e., both the dose at 1 cm and the calibrating ion chamber are insensitive to low-energy electrons). Using the tissue-equivalent extrapolation chamber, the shallow dose rate (0.007 cm tissue depth) was measured to be approximately 5% higher than the deep dose rate (1 cm tissue depth). While draft ANSI N13.11 quotes the same exposure-to-dose conversion factor for both depths, it states in Appendix C that the shallow depth value was chosen arbitrarily. The increase in dose rate at the shallow depth is attributed to scattered radiation from the source and collimator assembly.

Assuming that the various contributions to the uncertainty are independent, the total uncertainty was 4% for the ^{137}Cs irradiations.

4.2.2 X Rays

Uncertainties for x-ray irradiations differed in only a few areas relative to the ^{137}Cs irradiations. Irradiation reproducibility was estimated at 2% based on the long-term variability of transmission-chamber calibration factors. This was attributed to differences in machine operating parameters. Dosimeter positioning errors were dominated by beam nonuniformity. Typically there was an absolute deviation of up to 5% over the dosimeter irradiation area. The variance due to scattered radiation was difficult to quantify. The measured photon spectra of K-fluorescent x-ray beams have very little contribution from scattered photons. Because similar geometries were used, the filtered beams should also have very little scatter.

The effect of mutual interaction for simultaneously irradiated dosimeters was checked at effective energies of 32 keV and 167 keV. Maximum differences in given dose were measured to be 1.5% and 2%, respectively.

The total uncertainty for x-ray irradiations was 4%.

4.2.3 $^{90}Sr/^{90}Y$

The greatest uncertainty for beta irradiations was the NBS calibration of absorbed dose to tissue at 35 cm for a $^{90}Sr/^{90}Y$ source. The primary reason for the large uncertainty was the lack of resources to develop improved capabilities due to the low demand for beta calibrations. Scientists at NBS recommended that, as an interim means, the laboratory standard for beta dosimetry be switched to the beta secondary standard carrying calibration certificates from the PTB. The given doses used for the test evaluations were corrected accordingly. The uncertainty in using the extrapolation chamber as a calibration transfer instrument between beta sources was 2%. The nonuniformity of the $^{90}Sr/^{90}Y$ sphere source used for routine irradiations was less than 2%. The effects of scattered radiation from the source support hardware or room surfaces were measured using a thin-window ionization chamber and were negligible. The total uncertainty was 6% or 4% for irradiations based on the NBS- or PTB-calibrated $^{90}Sr/^{90}Y$ source, respectively.

4.2.4 ^{252}Cf

The quoted uncertainty in the emission-rate calibration performed by NBS was 1.2%. Phantom positioning and dosimeter placement uncertainties were estimated at approximately 1% each. The correction to the dosimeter response for neutron scattering varies from approximately 6.5% for an albedo dosimeter to 1.3% for a rem-response dosimeter. Data taken with the Hanford albedo design was used to help estimate the uncertainty for scatter corrections. The total uncertainty for ^{252}Cf irradiations was 4% and 3% for albedo dosimeters and rem-responding dosimeters, respectively.

5.0 CALCULATION OF GIVEN DOSE EQUIVALENTS

5.1 ^{137}Cs SOURCE

The ^{137}Cs source was calibrated for exposure in free air. The given dose equivalent was calculated by

$$H = C_x \dot{X}_{air} t$$

where

H = given dose equivalent at either the shallow or the deep depth (mrem)

C_x = the exposure-to-dose equivalent conversion factor specified in ANSI N13.11 (= 1.03 mrem/mR for both depths)

$\dot{X}_{air}$ = exposure rate in air, measured at the calibration point (mR/min)

t = irradiation time (min).

5.2 X-RAY BEAMS

The x-ray beams were calibrated for exposure in free air. The given dose equivalent was calculated by

$$H = C_x T M C_{tp}$$

where

C_x = the exposure-to-dose equivalent conversion factor specified in draft ANSI N13.11 for either the nearly monoenergetic beams or the NBS filtered beams (mrem/mR)

T = the exposure-rate calibration factor for the transmission ionization chamber, at the standard temperature and pressure, measured at the calibration point (mR/C)

M = the reading of the transmission chamber (C)

C_{tp} = temperature and pressure correction factor for the transmission chamber reading.

5.3 BETA SOURCES

The beta sources were calibrated in absorbed dose at a tissue depth of 0.007 g/cm^2. The given dose equivalent is calculated by

$$H = D_t \; t \; Q$$

where

D_t = the absorbed dose rate (mrad/h) at 0.007 g/cm^2 depth in tissue, measured at the calibration point with additional source filtration when appropriate

t = irradiation time (h)

Q = the quality factor for beta particles (1 mrem/mrad).

5.4 ^{252}Cf SOURCE

The ^{252}Cf source was calibrated at NBS for neutron emission rate. The free-field given dose was calculated by

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

where

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

C_N = The dose-equivalent conversion factor (mrem-cm^2/n). The 1978 draft of ANSI N13.11 specifies 3.4×10^{-5} mrem-cm^2/n. The most recent value is 3.33×10^{-5} mrem-cm^2/n (Schwartz and Eisenhauer 1982).

t = the irradiation time (h)

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

3600 = seconds per hour

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