

Measurements and Characterization of Neutron and Gamma Dose Quantities in the Vicinity of an Independent Spent Fuel Storage Installation

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ABSTRACT

As part of the decommissioning of the Maine Yankee Atomic Power Company (MYAPCo) nuclear power plant, the spent nuclear fuel is being temporarily stored in a dry cask storage facility on a portion of the original licensed property. Each of the spent nuclear fuel (SNF) storage casks hold approximately 25 spent fuel assemblies. Additional storage casks for the greater-than-Class C waste (GTCC) are also used. This waste is contained in 64 casks (60 SNF, 4 GTCC), each of which contain a substantial amount of concrete for shielding and structural purposes. The vertical concrete casks (VCCs) are typically separated by a distance of 4 and 6 feet. The storage casks are effective personnel radiation shields for most of the gamma and neutron radiation emitted from the fuel. However measurable gamma and neutron radiation levels are present in the vicinity of the casks.

In order to establish a controlled area boundary around the facility such that a member of the public annual dose level of 0.25-mSv¹ could be demonstrated, measurements of gamma and neutron dose equivalents were conducted. External gamma exposure rates were measured with a Pressurized Ion Chamber (PIC). Neutron absorbed dose and dose equivalent rates were measured with a Rossi-type tissue equivalent proportional counter (TEPC). Both gamma and neutron measurements were made at increasing distances from the facility as well as at a background location.

The results of the measurements show that the distance to the 0.25-mSv per year boundary for 100% occupancy conditions varies from 321 feet to 441 feet from the geometric center of the storage pads, depending on the direction from the pad. For the TEPC neutron measurements, the average quality factor from the facilities was approximately 7.4. This quality factor compares well with the average quality factor of 7.6 that was measured during a calibration² performed with a bare Cf-252 source.

¹ 40CFR190, see Reference 1

² PNNL Report of Calibration # 03243, see Reference 2

INTRODUCTION

Gamma and neutron dose rate measurements were performed onsite at MYAPCo to identify operational absorbed dose rates and dose equivalent rates in the vicinity of the ISFSI. The measurements were performed to identify operational dose rates in the vicinity of the ISFSI following the placement of the vertical concrete casks (VCCs).

The overall goal of these measurements was to characterize the total dose equivalent rate as a function of distance from the ISFSI array. Results of these measurements will assist MYAPCo in identifying the 0.25-mSv/yr boundary imposed by 10CFR72.104³ and demonstrate compliance with 40CFR190⁴. The measurements were designed to identify the gamma and neutron components of the absorbed dose and dose equivalent rates. Other dose related quantities, determined as part of these measurements, included absorbed dose and dose equivalent, neutron-to-gamma ratios, and neutron quality factors.

METHODOLOGY

In order to profile the dose response as a function of distance from the center of the VCC array several measurement schemes were employed. At each measurement location a global positioning system (GPS) was used to identify the spatial coordinates to allow for 2-dimensional graphical representation of the data. Measurements were performed in the immediate vicinity of the ISFSI, or nearfield. These measurements were performed on and around the ISFSI pad and also included locations along the security and industrial area fences. Nearfield measurements were also performed as a function of distance in sectors coincident with both the long and short axis of the VCC array. Measurements were also performed in sectors that included the corners of the industrial fence. These nearfield measurements were generally performed to provide high signal-to-noise ratio data to serve as input to the total dose response as a function of distance, specifically to observe the decrease in dose rate as a function of distance from the center of the VCC array.

Downfield measurements were performed at distances that ranged from 100 to 300 meters from the center of the ISFSI array. Nearfield and downfield measurements performed as a function of distance in sectors coincident with the long and short axis of the VCC array were used to estimate the 0.25 mSv/yr boundary.

All measurement results were corrected for ambient background. Gamma exposure rate results were corrected using ISFSI pre-loaded survey data. Neutron dose equivalent rates were corrected based on an off-site background measurement performed at an environmental monitoring station, located approximately 8 miles north of the ISFSI.

Gamma Instrumentation

External gamma exposure rates were measured with a Reuter-Stokes Model RS-111 Pressurized Ion Chamber (PIC). The PIC is comprised of an 8-liter steel, spherical ionization chamber filled to a pressure of 2.53×10^6 Pa (absolute) with ultra-high purity argon⁵. Advantages of this type of detector include; an

³ see Reference 3

⁴ see Reference 1

⁵ GE Reuter Stokes User's Manual, see Reference 4

omni-directional or isotropic response; high sensitivity to penetrating radiation; well-characterized fill gas (argon); and a flat energy response near unity.

The reported exposure rates from the PIC measurements are based on the mean of nominally ten 30-second measurements. The quoted random uncertainty is the 1- σ standard deviation of the measurements and provides an estimate of the measurement precision. The overall uncertainty of this technique is ± 5 percent⁶. Dose equivalent rates were based on a quality factor of 1.

The PIC was calibrated with a National Institute of Standards (NIST) traceable Cs-137 source by the original equipment manufacturer (OEM) using the shadow shield technique⁷. The calibration is normalized to the response of Ra-226, which has photon emissions in the 200 to 2000 keV range.

All PIC exposure rate results were corrected by subtracting the average pre-operational exposure rate to determine the net exposure rate attributed to ISFSI load operations. The pre-operational exposure rates ranged from 0.091 to 0.125, $\mu\text{Sv/hr}$ and were normally distributed about the mean value of 0.109- $\mu\text{Sv/hr}$. The standard deviation of the mean for the pre-operation exposure rate was 0.01- $\mu\text{Sv/hr}$ or 9%. The pre operational survey consisted of 21 survey locations within a nominal radius of 300 meters of the ISFSI array.

Neutron Instrumentation

The HAWK TEPC is a sealed spherical TE proportional gas counter, Rossi type, enclosed in a stainless steel cylindrical housing⁸. The detector shell wall is a hollow sphere of A150 conducting tissue-equivalent (TE) plastic with a wall thickness of 0.21 centimeters. The fill gas is TE propane that simulates tissue with a 2- μm site size at 7-Torr pressure. The cylindrical stainless steel housing is 2 mm thick. Advantages of this type of detector for measuring the neutron environment include: an omni-directional or isotropic response; high sensitivity to neutrons over a wide energy region; capability to quantify absorbed dose, dose equivalent, and quality factors; and a relatively flat energy response. The detector electronics include 2 multi-channel analyzers (MCA). The high gain MCA (256-channel) accumulates linear energy transport (LET) spectra in the 0 to 25.6-keV/ μm range while the low gain MCA (1024-channel) stores LET data from 0 to 1024-keV/ μm .

For x-ray and gamma radiation greater than 0.5-keV/ μm , the TEPC measures the absorbed dose from secondary electrons recoiled into the chamber from the TE plastic walls. The Bragg peak associated with these secondary electrons has a maximum lineal energy of 10 to 15-keV/ μm ⁹. For fission neutron sources, the majority of the neutron dose events occur at an LET greater than 10 to 15-keV/ μm . The dose from photon and neutron components can be separated based on the neutron threshold LET.

For neutrons with incident energy greater than 20-keV, the TEPC measures the absorbed dose directly from the secondary protons and heavy nuclei recoiled into the chamber from the TE plastic walls. Low energy and thermal neutrons interact by the following reactions:



The 580-keV protons and 2.2-MeV photons resulting from these reactions are the major contributor to dose in tissue from neutrons in the thermal energy range. Pulse height analysis on the secondary particle events results in the LET spectrum which is characterized by regions that can be identified as originating

⁶ HASL-260, see Reference 5

⁷ GE-Reuter Stokes Manual, see Reference 4

⁸ HAWK TEPC Manual, see Reference 6

⁹ ICRU-1983, see Reference 7

from specific recoil particles. Pulse height analysis enables the system to discriminate between pulses from secondary particles due to neutrons or gamma interactions. The TEPC directly measures the absorbed dose as a result of these reactions for thermal neutrons. By evaluating the lineal energy spectrum, and thus Q, the neutron dose equivalent can be obtained directly. Since the Quality Factor (Q) is a function of the lineal energy, Q can be directly determined and combined with the neutron absorbed dose to provide the neutron dose equivalent. Because TEPC analysis uses the lineal energy of the secondary particles detected to obtain an average Q, they are essentially neutron energy independent in the range of thermal neutrons up to about 20-MeV. This is an advantage over moderator type neutron detectors which are dependent on neutron energy.

The TEPC was calibrated using NIST traceable sources by the original equipment manufacturer (OEM). The neutron radiation fields were moderated and un-moderated spontaneous fission neutrons from Cf-252. The un-moderated Cf-252 source produces a neutron spectrum with an approximate average energy of 2.2-MeV. The gamma radiation field calibration was performed using a nominal 370 GBq Cs-137 source. The radiation field is calibrated to an approximate distance of 6 meters in terms of $\mu\text{R/h}$ using an air ionization chamber with a calibration traceable to NIST.

By default, the HAWK TEPC uses ICRP-60¹⁰ quality factors and ICRP-74¹¹ dose equivalent quantities to convert absorbed dose-to-dose equivalent quantities. The HAWK TEPC was designed for the international community and these are the relevant quality factors and dose equivalent quantities. US standards and regulations¹² are based on ICRP-21¹³ quality factors and ICRP-26¹⁴ dose equivalent quantities. To evaluate the effect of applying these different factors, the TEPC was calibrated at the Pacific Northwest National Laboratory¹⁵. Results of this calibration indicated differences associated with the reported dose equivalent response of the instrument depending on the source of the quality factors (ICRP-21 versus ICRP-60 methodology). Using ICRP-21 quality factors, dose equivalent results are within 7% of the irradiated value. Using ICRP-60 quality factors and ICRP-74 dose equivalent quantities, the HAWK TEPC was observed to over-respond by a factor of 1.6. This over response is attributed solely to differences in quality factors in the LET energy range of the Cf-252 spectra. For these ISFSI measurements, the ICRP-21 and ICRP-26 methods were used to report absorbed dose, quality factor and dose equivalent rate quantities.

RESULTS AND DISCUSSION

Measurements were performed with the center of the PIC or TEPC at 1-meter above the ground surface plane. Results for both detectors are based on multiple measurements at each location. PIC measurement results are typically based on measurements performed over a 5-minute time period. TEPC measurement results required measurement times that typically ranged from 15 minutes to 3-hours.

All TEPC LET event spectra were corrected for ambient background collected from an offsite control station. The TEPC background was accumulated for nominally 4 hours, which provided a neutron background measurement precision on the order of 20%. The ambient background LET spectra was subtracted from each measurement LET spectra, on a channel-by-channel basis. Quality factors were determined based on the net LET event spectra. The measurements were analyzed using a neutron threshold LET of 20-keV/ μm , based on the results of supplemental measurement performed on concrete casks that only contained highly irradiated components (Greater than Class C Waste, or GTTC) as these do not emit neutron radiation.

¹⁰ ICRP-60, see Reference 8

¹¹ ICRP-74, see Reference 9

¹² 10CFR20, see Reference 10

¹³ ICRP-21, see Reference 11

¹⁴ ICRP-26, see Reference 12

¹⁵ PNNL Report of Calibration # 03243, see Reference 2

ISFSI Site Measurements

Gamma and neutron dose rate surveys were performed in the vicinity of the ISFSI following the placement of 64 VCCs. Gamma exposure rates were measured using the PIC at a total of 169 locations. The gamma measurements were corrected for pre-load ISFSI ambient background.

Eighty-eight (88) gamma measurements were performed in the immediate vicinity (nearfield) of the ISFSI. Twenty-four (24) of these measurements were performed in a sector coincident with the long axis of the VCC array. Twenty-three (23) measurements were performed in a sector coincident with the short axis of the VCC array. Twenty-six (26) measurements were performed on the ISFSI berm with a direct line of sight (LOS) to the VCC array. Twenty-nine (29) measurements were performed beyond the berm with no direct LOS. Fig. 1 is a spatial overview of a portion of the nearfield measurement data set showing the gamma dose equivalent rates in units of $\mu\text{rem/hr}$. The measurement results show the gamma dose equivalent rate ranged from background, to approximately 50- $\mu\text{Sv/hr}$, depending on proximity to the storage casks.

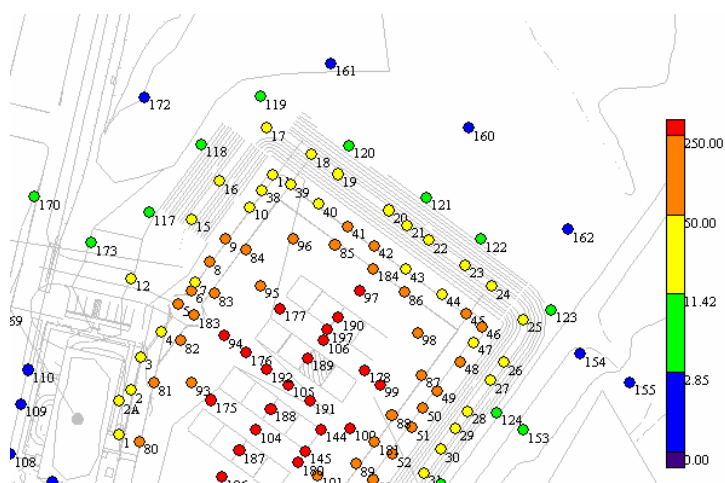


Fig. 1. Example of nearfield spatial gamma dose equivalent results ($\mu\text{Sv/hr} \times 10^2$)

Neutron radiation levels were measured using the TEPC at a total of 55 locations. Net neutron absorbed dose rates ranged from background to 0.110- $\mu\text{Gy/hr}$, in the general area of the ISFSI. Corresponding net neutron dose equivalent rates ranged from background to 0.902- $\mu\text{Sv/hr}$, in this same area. Net neutron absorbed dose rates ranged from 0.104 to 0.360- $\mu\text{Gy/hr}$, on the VCC pads in the vicinity of the high decay heat VCCs. Corresponding net neutron dose equivalent rates ranged from 0.652 to 2.896- $\mu\text{Sv/hr}$, at these same locations.

The total dose equivalent rate profile along the center of the VCC array short axis is plotted in Fig. 2 and Fig. 3. Included in these figures is the 2- σ error in the total dose equivalent rate plotted as error bars. The 2- σ error was calculated by adding the neutron and gamma dose equivalent error rates in quadrature sum. Fig. 3 is an expanded view of the VCC array short axis profile. The 0.25-mSv/yr boundary is estimated to occur at about 134-meters west of center on the VCC array short axis based on linear interpolation. On the east side, the 0.25-mSv/yr boundary is interpolated to extend to nominally 98-meters.

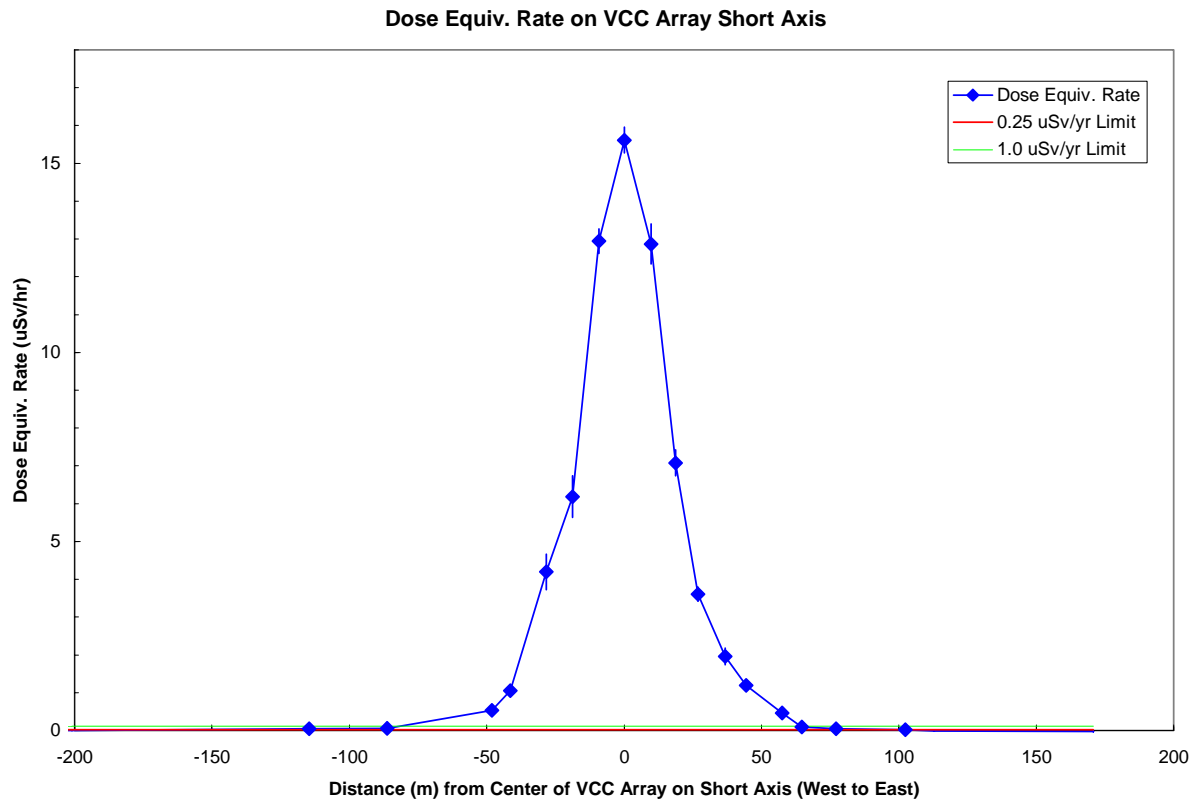


Fig. 2. Total dose equivalent rate ($\mu\text{rem/hr}$) on VCC array short axis

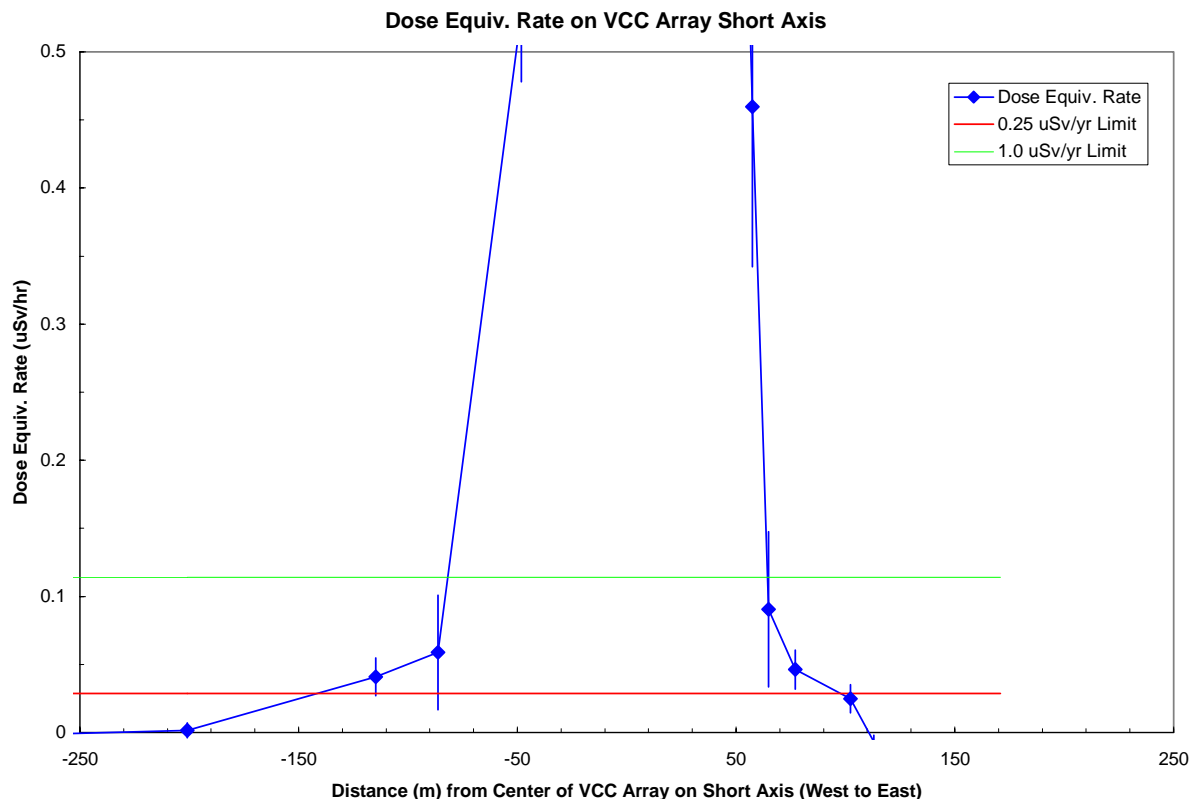


Fig. 3. Expanded view of total dose equivalent rate ($\mu\text{rem/hr}$) on VCC array short axis

The estimated 0.25-mSv/yr boundary estimated by interpolation for each side of the long and short axis is summarized as follows:

Table I. Distance to 25-mrem/yr from Center-of-ISFSI Array

Boundary	Axis	Distance to 0.25-mSv/yr from Center-of-ISFSI Array, m
South	Long	-115.7
North	Long	109.0
West	Short	-134.5
East	Short	98.0

Supplemental Measurements

Several measurements were subsequently performed at another ISFSI site which provide additional mixed field (neutron and gamma) information that were used to aid in the interpretation of the TEPC LET event spectra. Measurements were performed in the immediate vicinity of two (2) as-like GTCC loaded casks to evaluate the endpoint of the LET spectra associated with the x-ray and gamma only component of the absorbed dose. These GTCC casks were the only VCCs loaded on the ISFSI at the time of the

measurements. Results of these measurements indicate that a portion of the gamma LET component extends as high as 20-keV/μm LET.

The default operation of the TEPC infers that dose events with an LET greater than 10-keV/μm, are treated as neutrons (i.e., assigned neutron quality factors). The number of neutron-dose events, are expected to be overestimated in the 10 to 20 keV/μm LET range since approximately 3 to 5% of the gamma component spills into this range. Neutron quality factors in the 10 to 20-keV/μm LET range from 1 to 3.7 based on ICRP-21 methodology and from 1 to 4.2 based on ICRP-60. Neutron quality factors in the LET range of 20 to 150-keV/μm typical of Cf-252, range from about 4 to 18 (ICRP-21) and from 4 to 30 (ICRP-60). Gamma events in the 10 to 20-keV/μm LET range that are interpreted as neutron events will cause the derived neutron quality factor, based on the dose equivalent-to-absorbed dose ratio, to be underestimated.

Additional TEPC measurements were performed in the vicinity of a nominal 8-MW_{th} SNF transfer cask during dewatering operations. The measurements were performed over a 14-hour period to evaluate the neutron LET spectra during dewatering operations. The transfer cask does not include concrete shielding and provides additional high signal-to-noise LET spectral information for a typical SNF. A long measurement was also performed in the immediate vicinity of a nominal 8-MW_{th} thermal load SNF after placement in a VCC. The measurement was performed over a 48-hour time period to provide a high signal-to-noise example of the neutron LET spectra in the vicinity of a typical SNF VCC.

Some dose quantity results from these measurements are summarized in Table II. Neutron-to-gamma ratios on a dose event basis varied by a factor of 6 over the range of measurements with the highest ratios observed during the SNF dewatering field and farfield measurements. Neutron-to-gamma ratios on a absorbed dose and dose equivalent basis varied by a factor of about 25 over the range of measurements. Neutron quality factors exhibited the smallest amount of variability on the order of 10% during the range of measurements.

Table II. Neutron and Gamma Dose Quantity Summary

Dose Quantity	SNF (Dewatering)	SNF VCC (Vent Port)	SNF VCC (Nearfield, Farfield)
n/γ dose event ratio	< 0.003	0.003	.0005
n/γ absorbed dose ratio	0.17	0.008	0.02
n/γ dose equivalent ratio	1.73	0.07	0.1
neutron quality factor	8.0	7.4	7.1

Conclusions

Neutron and gamma dose rate surveys were performed in the vicinity of the MYAPCo ISFSI. During the survey, the ISFSI contained a total of 64 VCCs, including 60 spent nuclear fuel (SNF) and 4 greater-than-class C (GTCC) waste casks. The measurements characterize the total dose equivalent rate as a function of distance from the ISFSI array. The measurements methods effectively quantified the gamma and neutron components of the absorbed dose and dose equivalent rates. The 0.25-mSv/yr boundary estimated by interpolation for each side of the long and short axis extend to distances of approximately 116 m for the long axis and 134 m for the short axis. The dose measurement results were based on ICRP-21 quality factors.

Two important observations were obtained from supplemental measurements. The SNF transfer cask and long SNF VCC measurements suggest that SNF neutrons are nominally similar to Cf-252 LET spectra as

calibrated, based on the observed quality factors. Additionally, the GTTC VCC scans demonstrate that the neutron LET threshold should be increased from 10 to 20-keV/ μm , in order to accurately discriminate neutron dose events from gamma dose events. Accurate discrimination of neutron and gamma dose events results in more realistic estimates of the dose equivalent quantities.

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