VALIDATION TESTING OF ANSI/IEEE N42.49 STANDARD REQUIREMENTS FOR PERSONAL EMERGENCY RADIATION DETECTORS

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Abstract—**Various radiation detectors including electronic personal emergency radiation detectors (PERDs), radiochromic film cards and thermoluminescent dosimeters (TLDs) were used to validate a subset of the radiological test requirements listed in the American National Standards Institute/The Institute of Electrical and Electronic Engineers (ANSI/IEEE) N42.49 standard. The subset of tests included the following: comparing the readout of the detectors with the value given at the National Institute of Standards and Technology (NIST); testing of the alarm settings (when applicable) in air-kerma (or exposure) and air-kerma rate (or exposure rate) mode; and investigating the effect of testing the detectors mounted on a phantom and free in air. The purpose of this work was not to test the performance of the sample of detectors used. Instead, the detectors were used to validate the requirements of the written standard being developed. For this purpose, the performance and response of these instruments were recorded when placed in ^{137}Cs, and x-ray beams at different air-kerma rates and test conditions. The measurements described in this report were performed at the NIST x-ray and gamma-ray radiation calibration facilities. The data in this report provide a benchmark in support of the development of the ANSI/IEEE N42.49 standard.**
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INTRODUCTION

The American National Standards Institute/The Institute of Electrical and Electronic Engineers N42.49 standard (ANSI/IEEE 2010) was developed to meet the needs of emergency responders. This standard is different from other previously developed ANSI standards for homeland security applications in that several instrument categories are defined depending on their use. These instruments are expected to withstand more demanding environmental and mechanical test conditions. The main purpose of the electronic personal emergency radiation detectors (PERDs) is to provide users with an indication of when a radiation exposure or exposure rate is unsafe while performing their work.

In order to define the best test requirements for the development of the ANSI/IEEE N42.49 standard, we conducted measurements with various types of detectors in x-ray and gamma-ray beams. These measurements were not designed to evaluate the performance of the particular set of detectors used, but instead to validate the requirements included in the document standard. Performance of radiation detectors in accordance with other published ANSI standards has been reported previously (Pibida et al. 2005).

During the development of ANSI/IEEE N42.49 several issues arose concerning the requirements and test methods to be used to evaluate instrument performance. The main issues that required validation testing to determine the optimal testing parameters were:

- Alarm test requirement—The alarm thresholds and field values used during testing had to be defined;
- Accuracy test requirement—The instrument accuracy over a large range of exposure rate and exposure values had to be defined;
- Energy response requirement—The type of x-ray beam to replace ^{241}Am had to be determined, due to the increasing regulatory requirements of large ^{241}Am sources; and
- Exposure field requirement—The use of an appropriate phantom for the radiological tests had to be determined, if applicable.

Special attention was given to the last two items listed above. Regarding the third item, the initial draft of the ANSI/IEEE N42.49 standard required the use of a National Institute of Standards and Technology (NIST) M150 x-ray beam to replace testing with a ^{241}Am source. The NIST M150 beam has a broad energy spectrum

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resulting from moderate aluminum filtration. Another option was to use the heavily filtered NIST H100 beam that has an effective energy of 80 keV. The NIST H100 beam is a more appropriate spectrum due to its monoenergetic qualities; however, the effective energy does not approximate the ^{241}Am main gamma line at 60 keV. The final option was the use of the International Organization for Standardization (ISO) 4037 narrow spectrum NS80 with an effective energy of 65 keV. Given these several possibilities, we conducted several measurements using different x-ray beam qualities to help decide what would be the best alternative to ^{241}Am.

Another important consideration during the development of the standard was the last item on the list above. That is, should PERDs be placed on a phantom when tested in a radiation field or calibrated free in air? PERDs are designed to be worn on the human body. Under these conditions, the instrument readout will be the result of two contributions when placed in a radiation field. The main contribution is from the radiation surrounding the detector in the absence of the human body. A second much smaller contribution can be due to the radiation backscattered from the human body back into the detector. This second contribution will depend strongly on the radiation type and energy, the type of detector and the wall material and thickness of the detector. To address the question regarding the use of a phantom for testing PERDs with photons, various detectors were tested with and without a phantom. In this investigation the effect of the phantom on different types of detectors was determined from the measurements.

EXPERIMENTAL SETUP

The measurements described in this report were performed at the NIST x-ray and gamma-ray radiation calibration facilities. These facilities provide beams of x rays and gamma rays that have been characterized in terms of the quantities air-kerma and exposure. The details about the NIST calibration facilities have been reported elsewhere (Lamperti and O'Brien 2001; Minniti 2003; Minniti and Seltzer 2007).

Various types of radiation detectors were tested in this work including Geiger Muller (GM) tubes, silicon diode and scintillator detectors, and radiochromic film cards and thermoluminescent dosimeters (TLDs). Not all instruments were used for all tests.

To evaluate the various requirements in the ANSI/IEEE N42.49 standard, the response of the instruments tested was measured by computing the ratio between the instrument reading and the NIST air-kerma as follows:

$$R = \frac{M}{K_{\mathrm{NIST}}}, \quad (1)$$

where K_{NIST} represents the value of the NIST air-kerma measured in units of gray (Gy), M is the instrument reading expressed in units of Gy, and R is the response of the instrument and is a dimensionless parameter. Note that the inverse of the response R is what is known within the user community as the detector calibration factor. For instruments reading in air-kerma units (Gy), the evaluation of eqn (1) was straightforward. However, for instruments reading in other radiation units such as exposure (in R) or dose equivalent (in Sv), a conversion was applied to express M in units of Gy. For example, an instrument reading that measured in units of R and denoted by $M(R)$ can be expressed in units of Gy by using the following relationship:

$$M(Gy) = 2.58 \times 10^{-4} M(R)\left(\frac{W}{e}\right)\left(\frac{1}{1-g}\right), \quad (2)$$

where $M(Gy)$ is the instrument reading expressed in units of Gy. *W/e* is the mean energy per unit charge expended in dry air by electrons, and g is the mean fraction of the initial kinetic energy of secondary electrons liberated by photons that are lost through radiative processes in air. The currently accepted g values for ^{137}Cs and x-ray beams are 0.0016 and 0.0000, respectively (Seltzer and Bergstrom 2003). The current value used by the NIST for *W/e* is 33.97 J/C, which is the value adopted by the international measurement system (Boutillon and Perroche-Roux 1987).

To test the response of the instruments to x rays, they were exposed to different radiation fields and beam qualities. The effective x-ray beam energies used were 65 keV and 80 keV, which correspond to beam qualities NS80 and H100, respectively. The air-kerma (exposure) rates used were 11.4 mGy h^{-1} (1.3 R h^{-1}) and 36.8 mGy h^{-1} (4.2 R h^{-1}) for the NS80 beam and 14.9 mGy h^{-1} (1.7 R h^{-1}) and 30.7 mGy h^{-1} (3.5 R h^{-1}) for the H100 beam. The NIST series of x-ray beam qualities are identified by a letter followed by a number; the letter indicates the degree of filtration and the number indicates the voltage applied to the x-ray tube in kilovolts. For the case of the ISO x-ray beam qualities, the letters preceding the voltage value refer to the width of the energy spectrum. The beam intensity was uniform within the surface area of instruments tested. Further information on the characteristics of the different beam qualities used can be found elsewhere (Lamperti and O'Brien 2001; ISO 1999).

The instruments were also tested in the NIST ^{137}Cs beam calibration facilities. The mean energy of the ^{137}Cs beam is 662 keV. The air-kerma rate delivered at the point of measurement was 110.6 mGy h^{-1} (12.6 R h^{-1}).

In addition to the accuracy tests, the alarm tests were performed according to the requirements of the standard. The integration time was selected to be 285.6 s in order to obtain a total accumulated air-kerma (exposure) of 8.78 mGy (1.0 R).

Both in the x-ray and gamma-ray beams, the detectors were tested free in air and mounted on a phantom. Special care was taken to align the instrument in all directions to ensure reproducibility of the measurements, to account for possible non-uniformities in the beam intensity. The detectors were placed at a distance of 1 m from the x-ray source and at 2 m from the ^{137}Cs source. The free in air measurements were performed by suspending the detectors free in air using packing tape only. The thickness of the packing tape was less than 0.1 mm and it was used to minimize any scattered radiation from the backing material into the detector. The measurements were later repeated by placing the detectors on a 30 cm × 30 cm × 15 cm polymethylmethacrylate (PMMA) slab. In both configurations the source to detector distance was the same. That is, the reference point of the detector was placed in both configurations at the same calibration distance. The reading of each instrument when exposed to radiation in the presence and absence of the PMMA phantom was obtained. The ratio of these readings allowed us to estimate the effect of the radiation scattered from the PMMA slab phantom back into the detector.

An important consideration for the GM-tube and silicon-diode type detectors was the design of the outer case. For example, a GM-tube enclosed in a metallic case that has a relatively thick wall will respond differently than one that has a thinner wall and/or made of a less dense material. The one with a thinner wall will be more sensitive to radiation scattered from the phantom back into the detector. The sample of instruments that was used in this study was a good representation of the various types of case designs that are commercially available. The subset included, as well, several instruments of similar construction allowing for the suspected observation of similar responses.

During the time period of all the measurements, the facility temperature was between 21°C and 23°C while the barometric pressure was between 99.99 kPa and 101.59 kPa.

RESULTS AND DISCUSSION

Table 1 shows a summary of the types of detectors that were used to validate the standard ANSI42.29. These included GM-tubes, scintillators, silicon-diodes, radiochromic film cards, and TLDs. Except for the case of the film cards, all other detector types were surrounded by an outer case or holder. The main material component of the detector housing is listed in Table 1. Also, the three lateral dimensions are given in the case of rectangular shaped devices. Two of the GM-type detectors had circular dimensions, one being designed as a wrist dosimeter. For these two detectors the diameter is provided instead. Each one of the TLDs used consisted of a circular chip made of LiF with a diameter of 3.8 mm. The material in front of the TLD chip consisted of a 0.5-mm-thick copper disc and a 3.0-mm-thick slab of plastic from the TLD holder. Also listed in Table 1 are the detection

Table 1. Instrument specifications.

ID	Detector type	Dimensions (mm)	Detector housing material	Readout units	Detection range
1	Si diode	48 × 78 × 9	Plastic	Gy h^{-1}, Gy	1 cGy h^{-1} to 10 Gy h^{-1}, 10 cGy to 10 Gy,
2	GM	76 × 54 × 17	Rubber and plastic	R h^{-1}, R	0.01 mR h^{-1} to 1,000 R h^{-1}
3 & 4	GM	100 × 66 × 29	Aluminum	Sv h^{-1} or R h^{-1}, Sv or R	1 μR h^{-1} to 500 R h^{-1}, 0.1 μR to 999 R
5	GM	55 diam., 20 thick	Plastic	Sv h^{-1}, Sv	1 μSv h^{-1} to 10 Sv h^{-1}, 1 μSv to 9.99 Sv
6	Si diode	78 × 62 × 22	Metallic alloy	Sv h^{-1} or rem h^{-1}, Sv or rem	0.1 mSv h^{-1} to 9.99 Sv h^{-1}, 0 μSv to 9.999 Sv
7	Si diode	72 × 60 × 21	Metallic alloy	Sv h^{-1} or rem h^{-1}, Sv or rem	0.1 mSv h^{-1} to 9.99 Sv h^{-1}, 0 μSv to 9.999 Sv
8	Si diode	78 × 62 × 22	Metallic alloy	Sv h^{-1} or rem h^{-1}, Sv or rem	0.1 mSv h^{-1} to 9.99 Sv h^{-1}, 0 μSv to 9.999 Sv
9	Si diode	48 × 86 × 9	Plastic	Sv h^{-1}, Sv	10 μSv h^{-1} to 10 Sv h^{-1}, 1 μSv to 10 Sv
10	Si diode	80 × 67 × 21	Metallic alloy	Sv h^{-1} or rem h^{-1}, Sv or rem	0.1 mrem h^{-1} to 300 rem h^{-1}, 0.1 mrem to 999 rem
11	CsI(TI) & pin diode	125 × 68 × 35	Rubber and plastic	Sv h^{-1} or R h^{-1}, Sv or R	0.01 Sv h^{-1} to 0.1 Sv h^{-1}, 0.01 μSv to 9.99 Sv
12	Film card	85 × 54 × 1	Not applicable	rads	10 color graded scale from 0 to 1,000 rads
13	GM	55 diam., 18 thick	Plastic	Sv h^{-1}, Sv	1 μSv h^{-1} to 10 Sv h^{-1}, 1 μSv to 9.99 Sv
14	TLD	3.8 diam., 0.4 thick	Plastic	Sv	10 μGy to 5 Gy
15	GM	96 × 61 × 31	Plastic	R h^{-1}, R	5 μR h^{-1} to 5 R h^{-1}

ranges for air-kerma (or exposure) and air-kerma rate (or exposure rate) as specified by the manufacturers of the instruments.

Figs. 1 and 2 summarize the results obtained with the two x-ray beam qualities NS80 and H100 and the ^{137}Cs gamma-ray beam. For a given radiation beam, the response *R* is plotted for each instrument and for two different air-kerma rates. For example, in Fig. 1, for the beam quality NS80, the responses of Instrument 11 are 1.65 and 1.4 for air-kerma rates of 11.4 mGy h^{-1} (1.3 R h^{-1}) and 36.8 mGy h^{-1} (4.2 R h^{-1}), respectively. The uncertainty bars for each data point shown in Figs. 1 and 2 represent the standard deviation of the mean in replicate measurements using the same instrument. When several instruments of the same model were used, the average value was plotted. Data points that do not show an uncertainty bar in all figures represent cases in which the measurement uncertainty is smaller than the symbol size.

Fig. 1 shows that all instruments have a different response with the NS80 and the H100 x-ray beams except for Instruments 5 and 6. This is observed when comparing the data points with different beam codes but a similar air-kerma rate. That is, the instrument response measured in the NS80 beam with an air-kerma rate of 11.4 mGy h^{-1} (1.3 R h^{-1}) should be compared with the

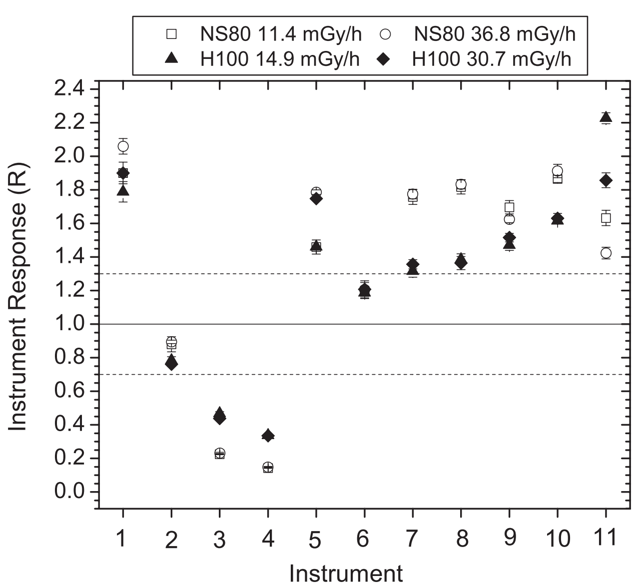

Fig. 1. Measured instrument response in the NS80 and H100 x-ray beams (detector readings are normalized to the NIST value). The relative response is shown for two air-kerma rates of 11.4 mGy h^{-1} (open squares) and 36.8 mGy h^{-1} (open circles) for the NS80 x-ray beam. The two air-kerma rates for the H100 beam used are 14.9 mGy h^{-1} (solid triangles) and 30.7 mGy h^{-1} (solid diamonds). All measurements were performed with detectors free in air, i.e., without being placed on a phantom. The dotted lines represent a variation of ±30%.

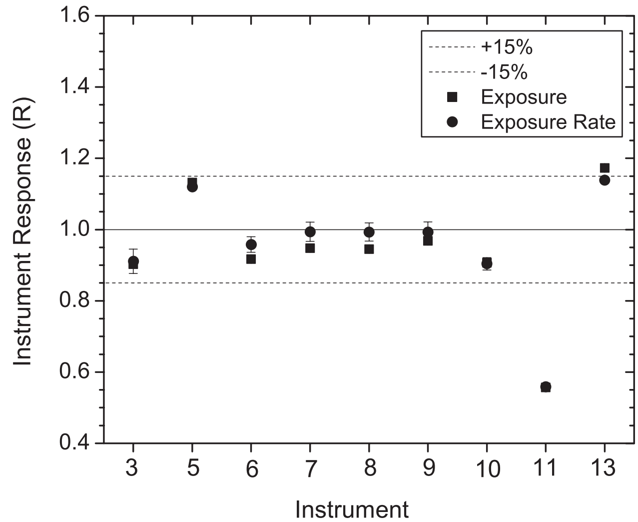

Fig. 2. Measured instrument response in the NIST ^{137}Cs beam (detector readings are normalized to the NIST value). Response was measured in rate mode (circles) and exposure mode (triangles). All measurements were performed with detectors free in air, i.e., without being placed on a phantom. The dotted lines represent a variation of ±15%.

H100 beam results with a similar air-kerma rate of 14.9 mGy h^{-1} (1.7 R h^{-1}). Except for Instruments 1, 5, and 11, all others show no dependence with air-kerma rate. In summary, Fig. 1 and Fig. 2 indicate that for most cases the response of the instruments clearly depends on the x-ray beam energy. Therefore, in deciding what beam quality should be used to replace ^{241}Am in the ANSI/IEEE N42.49 standard requirements, an x-ray beam with an effective energy closest to 60 keV should be considered. For ^{241}Am, the NS80 beam is the optimal choice with an effective energy of 65 keV.

A second item from the list of requirements in the ANSI/IEEE N42.49 standard that was investigated was the accuracy requirement of the air-kerma rate (exposure rate) and air-kerma (exposure) measurements. The air-kerma rate range of interest for these types of instruments is between 87.8 μGy h^{-1} (10 mR h^{-1}) and 2.63 Gy h^{-1} (300 R h^{-1}) for ^{137}Cs. To explore the accuracy of the instruments in this air-kerma rate (exposures rate) range, the detectors were exposed to a ^{137}Cs field of 0.11 Gy h^{-1} (12.6 R h^{-1}) and the results are shown in Fig. 2. As observed in Fig. 2, for most instruments tested, the requirement of an accuracy of ±15% proposed in the ANSI/IEEE N42.49 standard is achievable. During this test the alarm response was also verified by setting the alarm threshold to 80% of the values of the air-kerma rate and air-kerma used. For example, during the total air-kerma (or exposure) alarm test, if the total air-kerma delivered to an instrument was 12.5 mGy, the alarm threshold on the instrument was set at 10 mGy (1.14 R).

Similarly during the air-kerma rate (or exposure rate) alarm test, since the air-kerma rate was 110.6 mGy h^{-1} (12.6 R h^{-1}), the threshold was set to 88.5 mGy h^{-1} (10.1 R h^{-1}). Instruments 3, 5, 6, 7, 8, 9, 10, 11, and 13 alarmed immediately when the threshold value was reached. The alarms remained active until they were reset by the user in most cases. For two of the instruments (7 and 8), the alarm switched off automatically after 1 min from the time the alarm became active. All other instruments did not alarm. These observations were taken into account during the development of the document standard and, as a result, the alarms for PERDs were required to be reset manually by the user.

The last requirement from the ANSI/IEEE N42.49 standard that was investigated in this work was the effect of using a phantom for testing the instruments. For this purpose, a subset of the detectors was tested without and with the presence of a phantom placed behind them. The results are summarized in Tables 2 and 3 for x rays and ^{137}Cs, respectively. The detectors tested included four GM type (Instruments 2, 3, 5, and 15), two Si-diode types (Instruments 6 and 10), four radiochromic film cards, and 24 TLDs. The uncertainty of the measurements listed in Tables 2 and 3 correspond to one (coverage factor of k = 1) standard deviation of multiple measurements made with the same detector in the case of the GM and Si-diode type detectors. For the case of TLDs, the uncertainty corresponds to the standard deviation obtained from irradiating separately each one of the 24 TLDs. Similarly, the uncertainty for the radiochromic film card measurements is the standard deviation of measurements made with the four cards. Measurements were performed using a 16 bit scanner in conjunction with a 2D imaging software. Differences in the measurements with and without the phantom range from 1% to 35% depending on the detector tested and the beam quality used. The largest differences were observed when the detectors were tested with the NS80 x-ray beam quality. For example, the differences for instruments 2, 6, and 15 were 15%, 16%, and 18%, respectively. The differences between using and not using a phantom for these instruments were reduced to 9%, 8%, and 1% as expected when placed in a higher energy beam such as ^{137}Cs. Since the housing materials of all these detectors were different, the amounts by which these differences were reduced were also expected to vary. The main point, however, is to realize that among a variety of detectors with completely different design, differences of up to almost 20% were observed between testing the detectors mounted on a phantom or free in air. Tables 2 and 3 also list the differences observed for the case of radiochromic film cards exposed to the NS80 x-ray and ^{137}Cs gamma-ray beams. A difference of up to 35% was observed in the x-ray beam and it was reduced to 8% when exposed in the gamma-ray beam. The large difference observed with the lower energy x-ray beam was not surprising since there was no outer case or housing around the film. Therefore this made this type of detector more sensitive to radiation backscattered from the phantom. These values are consistent with published calculations of backscatter factors (Cohen et al. 1978). Calculated backscatter factors from Cohen et al. (1978) are between 1.37 and 1.49 for x-ray beams with half value layers similar to that of the NS80 beam used in this work. The value listed in Cohen et al. (1978) for ^{137}Cs is 1.07. It should be mentioned that a strict comparison should not be made with the published calculations since the beam geometries are not exactly the same. However, despite the beam geometry differences between the published calculations and the measurements, quite good agreement is observed within the uncertainty of the measurements.

The significant variations of up to 20% observed for the GM and silicone-diode type detectors and of 35% for the case of the film cards, between the tests made with and without a phantom, suggest that instruments cannot be tested free in air. The presence of the human body does have a significant effect on the reading of the detectors. Furthermore, the magnitude of the differences

Table 2. Ratios for NS80 x-ray beam measurements with and without phantom.

	Phantom/air ratio for NS80 x rays		
Instrument	Exposure rate	Exposure	Uncertainty[a] (%)
2	1.15	1.15	2.3
3	1.20	1.07	2.6
5	1.08	1.10	2.3
6	1.15	1.16	2.0
10	1.04	1.04	3.0
15	1.19	1.18	1.6
Film card	NA[b]	1.35	2.3

[a] Uncertainties shown in this table are for a coverage factor of k = 1.
[b] NA = not applicable.

Table 3. Ratios for ^{137}Cs measurements with and without phantom.

	Phantom/air ratio for ^{137}Cs gamma rays		
Instrument	Exposure rate	Exposure	Uncertainty[a] (%)
2	NA[b]	1.09	1.0
3	1.04	1.05	3.2
5	NA	1.09	2.2
6	1.08	1.08	2.2
10	1.11	1.11	2.4
Film card	NA	1.08	1.7
TLD	NA	1.09	1.0
15	NA	1.01	1.0

[a] Uncertainties shown in this table are for a coverage factor of k = 1.
[b] NA = not applicable.

of up to 20% observed between using or not a phantom are comparable to the accuracy requirement of the ANSI/IEEE N42.49 standard of ±15% for air-kerma rate (exposure rate) and air-kerma (exposure). Therefore, tests conducted free in air would result in inaccuracies that would be unacceptable based on the requirements outlined in the document standard. As a result of the measurements presented here, the use of phantoms for testing PERDS is recommended. Such recommendations were included in the document standard.

Another important observation was regarding the measurements made with the detector suspended free in air. These tests were made by suspending the detector in air using thin packing tape material only. Holding the detectors with a thin piece of plastic instead would result, for some instruments, in variations of up to 4% in the measurements for the low energy NS80 x-ray beam. This observation further supports using a phantom for testing instruments to better standardize the testing of instruments against the ANSI N42.49 standard. Free in air measurements could lead to the adoption of different procedures across testing facilities.

During these last series of tests performed with and without a phantom using the x-ray beam, it was observed that the measurements were quite sensitive to the alignment of the detectors relative to the source and beam centerline. To achieve reproducibility of the results, two reference marks were considered for each detector: one for the calibration distance and one for the height of the detector relative to the beam center line. In only a few cases, detectors were marked by the manufacturer with such reference points. In the cases that no marks were provided, reference marks were added and measurements were repeated always using such reference marks. It can be concluded from these tests that using reference marks for calibrating or testing instruments is of fundamental importance to achieve reproducible results over long periods of time.

CONCLUSION

Based on the test results of these measurements, several suggestions were made during the development of the ANSI/IEEE N42.49 standard. These can be summarized as follows: 1) The x-ray beam quality NS80 should be used for testing the instruments at low energies when there is a need to replace the ^{241}Am source; 2) The requirement of ±15% in the accuracy for the air-kerma rate (exposure rate) and air-kerma (exposure) is acceptable for these types of detectors; and 3) Based on this study it is recommended that the radiological test of PERDs be performed on phantoms to better simulate the real situation in which these devices are worn on the human body.

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