

American National Standard Performance Criteria for Alarming Personal Radiation Detectors for Homeland Security

Accredited by the American National Standards Institute

Sponsored by the
National Committee on Radiation Instrumentation, N42

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American National Standard Performance Criteria for Alarming Personal Radiation Detectors for Homeland Security

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Secretariat

Institute of Electrical and Electronics Engineers, Inc.

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Abstract: Minimum performance specifications and testing methods for the evaluation of alarming personal radiation detectors, also known as PRDs, are contained in this standard. These detectors are pocket-sized and carried on the body. These instruments are primarily designed for the detection and location of radioactive materials emitting gamma rays, and possibly neutrons, and not intended to function as electronic dosimeters. The specifications for general, radiological, environmental, electromagnetic, and mechanical performance are given, and the corresponding testing methods are described. The documentation to be provided by the manufacturer is listed as part of the requirements. A number of informative annexes that provide useful information and guidance in implementing this standard are also contained in this standard.

Keywords: alarming personal radiation detectors, ANSI N42.32, documentation, gamma-rays, information and guidance, neutrons, performance specifications and testing, pocket-sized, radiation, radiation detection, radiation detection instruments, radioactive material

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Introduction

This introduction is not part of ANSI N42.32-2016, American National Standard—Performance Criteria for Alarming Personal Radiation Detectors for Homeland Security.

This standard is the responsibility of the Accredited American Standards Committee on Radiation Instrumentation, N42. The standard was approved on N42 letter ballot.

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1. Overview

1.1 Scope

This standard describes minimum performance requirements and test methods for evaluating the performance of alarming personal radiation detectors (PRDs) for homeland security applications.

PRDs are pocket-sized battery-powered alarming electronic instruments that are worn on the body and used to detect photon-emitting, and optionally neutron-emitting, radioactive materials. PRDs have user-readable displays related to the intensity of radiation, but they are distinct from, and typically more sensitive than, electronic personal dosimeters, which are designed to measure the dose equivalent to workers occupationally exposed to radiation.

The performance criteria contained in this standard are meant to provide the means for verifying the capability of the PRDs to reliably detect changes above background levels of ionizing radiation fields and alert the user to these changes. This standard also specifies the requirements and test methods for environmental, electromagnetic, and mechanical conditions that may affect the ability of the PRDs to function properly.

This standard does not apply to spectroscopic PRDs that have the ability to identify radionuclides. The ANSI N42.48 standard [B12] covers spectroscopic PRDs.¹ This standard does not apply to instruments that

¹ The numbers in brackets correspond to those of the bibliography in Annex A.

are primarily intended to provide a measurement of dose-equivalent, personal dose-equivalent, or ambient dose-equivalent rate. However, if the manufacturers of PRDs that provide an indication of personal dose-equivalent rate (expressed in units of mrem/h or $\mu\text{Sv/h}$) claim that the PRD may be used for personal protection, then the PRD shall comply with the applicable radiological requirements described in ANSI N42.20 [B17] (i.e., accuracy, energy, and angle response tests).

1.2 Purpose

This standard specifies the performance requirements and test methods used to evaluate PRDs.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI N42.42, American National Standard Data Format for Radiation Detectors Used for Homeland Security.^{2,3}

IEC 60529, Degrees of protection provided by enclosures (IP Code).⁴

IEC 62706 (Ed. 1.0), Radiation protection instrumentation—Environmental, electromagnetic and mechanical performance requirements.

ISO 4037-3, X and gamma reference radiation for calibrating dosimeters and doserate meters and for determining the response as a function of photon energy—Part 3: Calibration of area and personal dosimeters and the measurement of their response as a function of energy and angle of incidence.⁵

3. Definitions, acronyms, and abbreviations

For the purposes of this standard, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁶

3.1 Definitions

A-weighted sound level: The frequency weighting of an acoustic spectrum according to a standardized frequency response curve based on the frequency response of the human ear.

acceptance test: Evaluation or measurement of performance characteristics to verify that certain stated specifications and contractual requirements are met.

accuracy: The degree of agreement between the observed value and the conventionally true value of the quantity being measured.

² The ANSI N42.42 schema can be obtained from <http://www.nist.gov/pml/div682/grp04/n42.cfm>.

³ ANSI N42 publications are available from the Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

⁴ IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch/>) and the American National Standards Institute (<http://www.ansi.org/>).

⁵ ISO publications are available from the International Organization for Standardization (<http://www.iso.ch/>) and the American National Standards Institute (<http://www.ansi.org/>).

⁶ *IEEE Standards Dictionary Online* is available at: <http://ieeexplore.ieee.org/xpls/dictionary.jsp>.

adjust: To alter the reading of an instrument by means of a built-in variable (hardware or software) control.

alarm: An audible, visual, or other signal activated when the instrument reading or response exceeds a preset value or falls outside of a preset range.

background radiation: Radiation present in the surrounding environment and emitted from soil, air, buildings, and other materials. Also present are photons and neutrons produced by the cosmic radiation.

calibrate: To adjust and/or determine the response or reading of a device relative to a series of conventionally true values.

calibration: A set of operations under specified conditions that establishes the relationship between values indicated by a measuring instrument or measuring system and the conventionally true values of the quantity or variable being measured.

coefficient of variation (V): The ratio of the standard deviation s to the arithmetic mean $\bar{x}$ of a set of n measurements, x_i , given by the following equation:

$$V = \frac{1}{\bar{x}} \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}$$

where

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

n is the number of test results
 x_i are the values of the test results

NOTE—For calculating V for instruments with unit-less displays, the reader should see Annex C of this standard.

conventionally true value (CTV): The commonly accepted best estimate of the value of that quantity.

NOTE—This quantity and its associated uncertainty will preferably be determined using a national or transfer standard, or by a reference instrument that has been calibrated against a national or transfer standard, or by a measurement quality assurance (MQA) interaction with the National Institute of Standards and Technology (NIST) or an accredited calibration laboratory. (See ANSI N42.22 [B1].)⁷

coverage factor: Numerical factor (k) used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty.

decade: A range of values for which the upper value is a power of 10 above the lower value.

detector: A device or component designed to produce a quantifiable response to ionizing radiation.

effective center: For a given set of irradiation conditions, the point within a detector where the response is equivalent to that which would be produced if the entire detector was located at the point.

effective range of measurement: Range of measurements within which the requirements of this standard are met.

⁷ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

energy dependence: Variation in instrument response as a function of radiation energy for a constant radiation type and measurement quantity.

exposure rate: The quantity of electric charge produced through the ionization of air by x-ray and/or gamma-ray radiation per unit mass of air per unit time. The exposure rate can be expressed as 2.58×10^{-4} C/kg in air per unit time.

NOTE—The special unit of exposure rate is the roentgen per hour, abbreviated in this standard as R/h.

false alarm: Alarm not caused by a radioactive source under the specified background conditions.

functional check: A frequently used qualitative check to determine that an instrument is operational and capable of performing its intended function.

NOTE—Checks may include, for example, battery check, zero setting, or radioactive source response check.

indicated value: (A) A scale or decade reading. (B) The displayed value of the readout. *See also:* **reading**.

indication: Displayed signal from the instrument to the user conveying information such as scale or decade, status, malfunction, or other critical information.

influence quantity: Quantity that may affect the result of a measurement without being the subject of the measurement.

instrument: A complete system consisting of one or more assemblies designed to quantify one or more characteristics of ionizing radiation or radioactive material.

monitoring: Means provided to continuously indicate the state or condition of a system or assembly.

NOTE—Monitoring may also be used for the real-time measurement of radioactivity or radiation levels.

over-range response: The response of an instrument when exposed to radiation intensities greater than the upper detection limit.

performance test: An evaluation of the performance of an instrument in response to a given influence quantity.

point of measurement: Place where the conventionally true values are determined and where the reference point of the instrument is placed for test purposes.

range: All measured values between the minimum statistically quantifiable instrument response (or reading) and the maximum level at which the instrument meets the required accuracy.

reading: The indicated or displayed value of the readout.

readout: The portion of the instrument that provides a visual numerical or other quantitative display of the response of the detector to radiation.

reference point of an instrument: Location within an instrument to be placed at the point of measurement. The reference point may be indicated by a physical mark or marks on the outside of the instrument. Its position may be clearly identifiable from the construction of the instrument or described in the instrument manual.

restricted mode: An advanced operating mode that can be accessed by an expert user (e.g., via password) to control the parameters that can affect the result of a measurement (i.e., radionuclide library, routine function control, calibration parameters, alarm thresholds).

NOTE—Restricted mode may be called the “advanced” or “expert” mode.

spurious indications: unexpected changes in the instrument response such as display changes (e.g., display going blank, part of the display not fully working), instrument switches off, a sudden increase in the instrument displayed readings, or modifications to the instrument settings.

standard deviation (s): The positive square root of the variance. The standard deviation can be evaluated using the following equation:

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}$$

where

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

n is the number of test results
 x_i are the values of the test results

standard instrument or source: (A) National standard—A standard determined by a nationally recognized competent authority to serve as the basis for assigning values to other standards of the quantity concerned. In the US, this is an instrument, source, or other system or device maintained and promulgated by the National Institute of Standards and Technology (NIST). (B) Primary standard—A standard that is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity. (C) Secondary standard—A standard whose value is assigned by comparison with a primary standard of the same quantity. (D) Reference standard—A standard, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made there are derived. (E) Working standard—A standard that is used routinely to calibrate or check material measures, measuring instruments, or reference materials. A working standard is traceable to NIST.

NOTE—See ANSI N42.22 [B1].

standard test conditions: The range of values of a set of influence quantities present when a calibration or a measurement of response is carried out.

test: A procedure whereby the instrument, circuit, or component is evaluated.

type test: Test of production instruments made to a specific design to show that the design meets defined specifications.

uncertainty: A parameter, reported with the result of a measurement that indicates a range of expected values associated with that measurement. The uncertainty may be expressed as a percentage or a multiple of the standard deviation of the distribution of measured values.

3.2 Acronyms and abbreviations

ESD	electrostatic discharge
HDPE	high-density polyethylene

IP	ingress protection
MQA	measurement quality assurance
NIST	National Institute of Standards and Technology
PMMA	polymethyl methacrylate
PRD	personal radiation detector
RF	radio frequency
RH	relative humidity

4. General considerations

4.1 Introduction

Unless otherwise specified in the individual steps, all tests enumerated in this standard are to be considered as type tests. Certain tests may be considered as acceptance tests by agreement between the customer and manufacturer.

It is recommended that testing facilities perform the tests in this standard in the following order to reduce potential damage to the PRD:

- General requirements
- Radiological tests
- Environmental tests except for moisture and dust tests
- Electrical and electromagnetic tests except the electrostatic discharge test
- Impact and the vibration tests
- Moisture and dust tests
- Electrostatic discharge test
- Drop test

All test results shall be documented.

4.2 Special word usage

The following word usage applies:

- The word “shall” signifies a mandatory requirement (where appropriate, a qualifying statement is included to indicate that there may be an allowable exception).
- The word “should” signifies a recommended specification or method.
- The word “may” signifies an acceptable method or an example of good practice.

4.3 Units and uncertainties

For the purposes of this standard, the radiological quantity of exposure rate in units of roentgens per hour (R/h), or subdivision thereof, shall be used for x-ray and gamma-ray radiation. The radiation field or exposure rate standard uncertainty should not exceed $\pm 20\%$; excluding radiation background measurements. If uncertainties are not specified for a measurable quantity, they are set to $\pm 15\%$. Unless otherwise stated, all uncertainties listed in the standard have a coverage factor of $k = 1$.

Radiation fields may be determined through measurements or calculations. Measurement of the radiation field should be performed using devices with a known energy response function and with a NIST traceable (or equivalent national metrology institute) exposure rate calibration. When radiation fields are determined through calculations, the technique and reference data (e.g., photon energies, emission probabilities, attenuation coefficients, absorption coefficients) used to determine the field and associated uncertainties should be recorded. Measurement of all influence quantity (i.e., environmental, electromagnetic, mechanical) values shall be made using calibrated equipment traceable to NIST (or equivalent national metrology institute).

For this standard, the radiological quantity of exposure rate (in units of R/h) is used for the determination of the x-ray and gamma-ray radiation field. If the device used to determine the radiation field measures ambient dose-equivalent rate [i.e., $H^*(10)$, in units of Sv/h or rem/h], the appropriate conversion coefficients shall be applied (see ISO 4037-3).⁸

Throughout the text, only exposure rate is expressed entirely in special non-SI units.

4.4 Standard test conditions

The required standard test conditions for environmental quantities, such as temperature and pressure, as well as those for other quantities that may influence the performance of PRD, are given in Table 1. These conditions shall be met, except where the effect of the condition or quantity itself is being tested (i.e., tests in Clause 7, Clause 8, and Clause 9). Environmental quantities, such as temperature and humidity, are referred to as influence quantities.

Table 1—Standard test conditions

Influence quantity	Standard test conditions
Stabilization time	As stated by the manufacturer
Ambient temperature	18 °C to 25 °C
Relative humidity (RH)	Less than 75%
Atmospheric pressure	70–106.6 kPa (525–800 mm of mercury at 0 °C)
Battery voltage	Voltage sufficient to keep the PRD out of any low-battery status for the duration of the test
Reference point	As marked on PRD or effective center of PRD
Angle of incidence of radiation ^a	Direction given $\pm 5^\circ$
Electromagnetic field of external origin	Controlled natural conditions without the presence of man-made generators. Devices with potential RF emission such as cell phones and Bluetooth [®] devices shall be kept at a minimum of 25 cm from the test instruments.
Magnetic induction of external origin	Controlled natural conditions without the presence of man-made generators
Instrument controls	Set up for normal operation as described in the PRD manual
Radiation background – gamma ^b	5–15 $\mu\text{R/h}$
Radiation background – neutron	≤ 200 neutrons/s/m ²
NOTE—The Bluetooth word mark is a registered trademarks owned by Bluetooth SIG, Inc. This information is given for the convenience of users of this standard and does not constitute an endorsement by the IEEE of this product. Equivalent products may be used if they can be shown to lead to the same results.	

^a This applies for the distance of closest approach and the setup of the PRD relative to the radiation field.

^b The level is representative of the values encountered in the environment where these devices are typically used.

⁸ Information on references can be found in Clause 2.

4.5 Background radiation during testing

Testing shall be performed in an area with a natural radiation background as defined in Table 1.

The gamma-ray background intensity shall be measured using a pressurized ion chamber or similar environmental radiation measurement device that is calibrated to provide the gamma-ray exposure rate. If the PRD is equipped with neutron detectors, the neutron background shall be the natural background and shall not be artificially modified during testing. The neutron background at the test location should be measured and recorded.

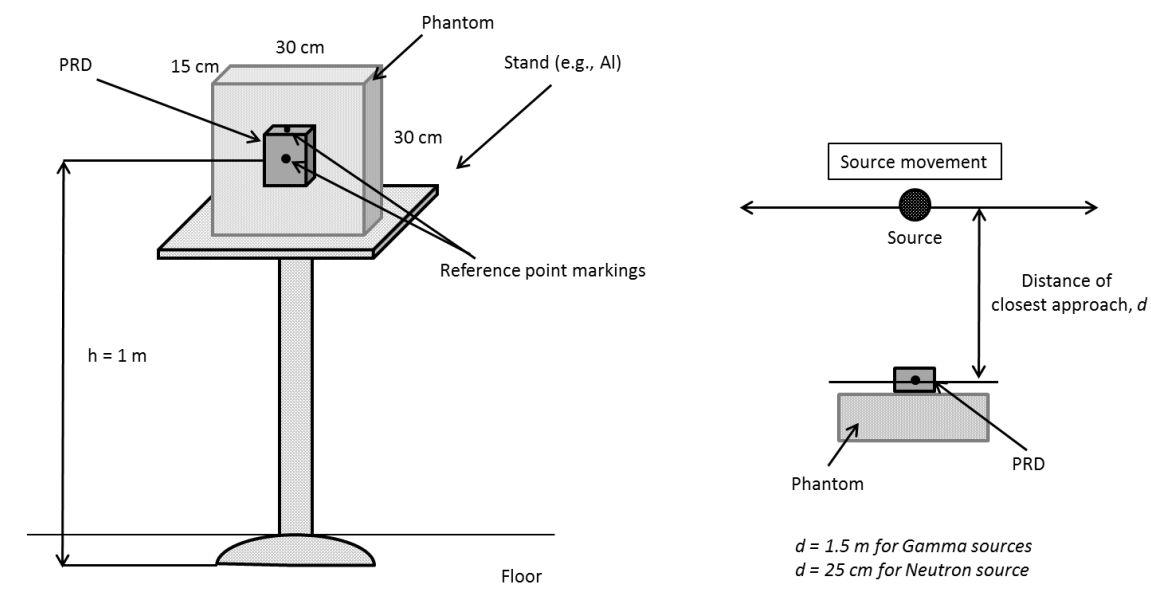
The evaluation of the PRD shall be performed without the benefit of any radiation shielding against the natural background, except for that shielding that is part of the instrument.

Background shall remain within the acceptable range, and the gamma-ray background shall not vary more than $\pm 5 \mu\text{R/h}$ for the duration of the false alarm test.

4.6 PRD setup

The PRD shall be set up based on the manufacturer's specifications including alarm thresholds and background update mode, if applicable. Once set up for testing, no changes shall be made that could affect the overall response of the PRD.

When performing the radiological tests in Clause 6, the PRD shall be configured and oriented as it would be used. This is achieved by using a phantom that would represent the human torso. The phantom shall be made of polymethyl methacrylate (PMMA). The phantom dimensions shall be 30 cm wide, 30 cm high, and 15 cm thick. The reference point of the PRD shall be centered on the phantom. The reference point of the PRD should be placed at a height of 1 m from the floor (see Figure 1). This PRD height may not be achievable for the accuracy test or the over-range test, in which case the actual testing height shall be recorded. The center of the radioactive source shall be placed at the same height as the reference point of the PRD.



The PRD together with the phantom shall be mounted on a stand or fixture made out of a material that does not have a large hydrogen content (e.g., aluminum, steel). It is recommended to use materials such as aluminum for mounting the PRD to prevent possible additional moderation of the neutron source. Materials with large hydrogen content may include foam and plastics.

The reference point of the PRD should be marked by the manufacturer. If marking or a description of the location of the reference point within the PRD is not provided by the manufacturer, the reference point is defined as the imaginary point where the three mutually orthogonal lines that go through the center of the length, width, and thickness of the PRD intersect.

When performing the tests in Clause 7, Clause 8, and Clause 9 (i.e., environmental, electromagnetic, and mechanical tests), the PRD shall not be mounted on a phantom. The PRD-to-source distance and the relative orientation and position between the PRD and the radiation source shall be adjusted to reduce the statistical fluctuations as discussed in 4.7. The testing distance, orientation, and position of the PRD with respect to source shall be recorded for these tests. Due to the nature of these tests, there is no need for this standard to specify the PRD-to-source distance and relative orientation and position between the PRD and the source, but they shall be the same for the pre-test and post-test measurements in order to obtain reproducible results (see 4.8).

For most tests, the PRD is required to stabilize before testing is carried out. The PRD is considered to be stabilized when it displays a message saying that the PRD is ready for use or after the required stabilization process described in manufacturer-provided documentation.

NOTE—Specific testing programs may require testing more than one unit for a given instrument model. This standard specifies the requirements for each PRD unit tested.

4.7 Statistical fluctuations

When performing environmental, electromagnetic, or mechanical tests, the magnitude of the statistical fluctuations of the PRD indication arising from the random nature of radiation alone should not be a significant fraction of the allowed variation (i.e., $\pm 15\%$).

The statistical fluctuations are measured by the coefficient of variation and, for the purposes of this standard, the coefficient of variation (V , expressed in percentage) for each nominal mean reading should be less than or equal to 8%. If the measured value of the coefficient of variation is larger than 8%, the exposure rate and/or neutron count rate should be increased (by using a larger source activity and/or reducing the source-to-PRD distance) to ensure that the mean value of such readings may be estimated with sufficient accuracy to demonstrate compliance with the test in question or by increasing the number of readings. If the number of readings is to be increased, see Table C.2 in Annex C.6 for guidance.

For measurements without radioactive sources (at background levels), the PRD is observed to verify that alarms and spurious indications are not produced by an influence quantity (e.g., temperature, humidity, RF, impact, vibration), as readings are expected to display large fluctuations. Therefore, testing without radioactive sources can be performed even when the coefficient of variation is larger than 8%, as for these measurements there is no need to determine the coefficient of variation.

NOTE—The time interval between readings needs be sufficiently long (i.e., larger than the integration time of the instrument) to ensure that the readings are statistically independent.

4.8 Functionality tests

For most tests in Clause 7, Clause 8, and Clause 9 (i.e., environmental, electromagnetic, and mechanical tests), the PRD functionality is evaluated prior to and after the test, and in some cases during the test as well. The PRD response after the test (post-test measurement) is compared with that measured prior to the

test (pre-test measurement). Therefore, the radioactive source location relative to the PRD reference point shall be the same for both the pre-test and post-test.

The gamma-ray measurements are performed using a ^{137}Cs source, producing an exposure rate of at least $50\ \mu\text{R/h}$ (above background) at the reference point of the PRD, unless otherwise stated in a test. The actual exposure rate value of the radiation field is not important for these tests as long as the radiation field is reproducible within $\pm 5\%$ between the pre-test and post-test.

The neutron measurements (if applicable) are performed using a ^{252}Cf source with an emission rate of $20\ 000\ \text{s}^{-1}$ (or greater) moderated by a 4 cm thick high-density polyethylene (HDPE) spherical container.

Statistical fluctuations should be considered during these tests (i.e., determination of coefficient of variation for the exposure rate or count rate readings of the PRD) in order to adjust the source-to-PRD distance or the source emission rate (see 4.7).

NOTE 1—If the PRD is equipped with a neutron detector, it is possible to have both sources placed in front of the PRD at the same time when taking the readings.

NOTE 2—The PRD could be attached to the HDPE sphere moderating the ^{252}Cf source in order to obtain the maximum possible neutron count rate reading and reproduce the radiation field within the requirements.

The pre-test and post-test measurements shall be carried out as follows in 4.8.1 and 4.8.2.

4.8.1 For PRDs with exposure or count rate displays

Pre-test

- a) Expose the PRD to the ^{137}Cs source, record 10 gamma exposure rate readings. The elapsed time between readings shall be greater than the PRD display update time or response time with a minimum of 2 s.
- b) Calculate the pre-test mean, $\bar{x}_{\text{pre}10}$, and pre-test standard deviation, $\bar{s}_{\text{pre}10}$, of the gamma exposure rate readings. Calculate the coefficient of variation (V) for the gamma readings using the following equation:

$$V = \frac{\bar{s}_{\text{pre}10}}{\bar{x}_{\text{pre}10}} \times 100$$

- c) If the coefficient of variation is less than or equal to 8%, then proceed to step d). Otherwise, make adjustments to increase the exposure rate according to 4.7 and return to step 1). If the exposure rate cannot be increased, then increase the number of required readings according to 4.7 and collect additional readings at the current exposure rate to satisfy the total required readings.
- d) Calculate the pre-test mean, $\bar{x}_{\text{pre}}$, and pre-test standard deviation, s_{pre} , of the gamma exposure rate readings.
- e) Verify that the gamma alarm is activated (increase the radiation field above the PRD gamma alarm threshold to verify the alarm response).
- f) If the PRD is equipped with a neutron detector, repeat pre-test step a) through step e) by exposing the PRD to the moderated ^{252}Cf source and recording the neutron count rate readings [step c)] and the neutron alarms [step e)]. The elapsed time between readings shall be greater than the PRD display update time or response time with a minimum of 5 s.

Post-test

- g) Place the same sources in the same location relative to the PRD as for the pre-test (the reproducibility of the radiation field should be within $\pm 5\%$ between the pre-test and post-test).
- h) Record the same information as in the pre-test step a) and step e). If the number of pre-test exposure rate readings was increased in step c), then the same number of readings shall be performed here.
- i) Calculate the post-test mean, $\bar{x}_{\text{post}}$, and post-test standard deviation, s_{post} , of the gamma exposure rate readings.
- j) Calculate the test statistics for the gamma exposure rate as shown in the following equations:

$$t_1 = \frac{\bar{x}_{\text{post}} - 0.85\bar{x}_{\text{pre}}}{\sqrt{\frac{s_{\text{post}}^2}{n_{\text{post}}} + \frac{(0.85 s_{\text{pre}})^2}{n_{\text{pre}}}}}$$

$$t_2 = \frac{\bar{x}_{\text{post}} - 1.15\bar{x}_{\text{pre}}}{\sqrt{\frac{s_{\text{post}}^2}{n_{\text{post}}} + \frac{(1.15 s_{\text{pre}})^2}{n_{\text{pre}}}}}$$

where

$n_{\text{pre}} = n_{\text{post}}$ = number of readings taken in each pre-test and post-test measurements, normally equal to 10 unless an increase in the number of reading was required.

NOTE—If $s_{\text{pre}} = s_{\text{post}} = 0$ then t_1 and t_2 are undefined. See acceptance criteria.

- k) If the PRD is equipped with a neutron detector, repeat post-test step g) through step j) by exposing the PRD to the moderated ^{252}Cf source and recording the count rate readings.
- l) Turn off the PRD, switch it back on, and verify that it goes through the self-check process and functions as described in the manufacturer's manual (e.g., provides a message indicating that the PRD is ready to perform a measurement).

4.8.2 For PRDs with unit-less displays

Pre-test

- a) Expose the PRD to the ^{137}Cs source, and record 10 gamma exposure rate readings. The elapsed time between readings shall be greater than the PRD display update time or response time with a minimum of 2 s.
- b) Determine an exposure rate and a standard deviation for each of the PRD's unit-less readings using guidance in Annex D and the manufacturer-provided conversion table.
- c) Calculate the mean ($\bar{x}_{\text{pre10}}$) and the standard deviation (s_{pre10}) of the set of 10 readings using the appropriate formula from Annex D.
- d) Calculate the coefficient of variation (V) using the following equation:

$$V = \frac{s_{\text{pre10}}}{\bar{x}_{\text{pre10}}} \times 100$$