Technical Capability Standard for Handheld Instruments Used for the Detection and Identification of Radionuclides

Domestic Nuclear Detection Office (DNDO)

Homeland Security

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Contents

Tables

1 Overview

1.1 Introduction

A Technical Capability Standard (TCS) is a government unique standard that establishes targeted performance requirements for radiation detection and non-intrusive imaging systems. The purpose of the TCS is to have, where practical, threat-informed unclassified standards for users with indicated test protocols for test organizations. Threat-informed is defined as based on a realistic threat interpretation as agreed to by the Technical Capability Standard Working Group (TCSWG). In support of this effort, unclassified detection capability benchmarks were established that do not compromise nuclear weapon design information.

It is anticipated that after a TCS is developed, the Domestic Nuclear Detection Office (DNDO) will work within the consensus standards arena to ensure the future American National Standards Institute/Institute of Electrical and Electronics Engineers (ANSI/IEEE) N42 series consensus standards reflect the capabilities described by the TCS benchmarks, where applicable.

Technical Capability Standards were developed by an inter-agency TCSWG. Membership of the TCSWG includes representatives from the Department of Homeland Security Domestic Nuclear Detection Office (DNDO), National Institute of Standards and Technology (NIST), Customs and Border Protection (CBP), the Nuclear Regulatory Commission (NRC), the Department of Energy (DOE), the Federal Bureau of Investigation (FBI), Office of Assistant Secretary of Defense for Homeland Defense and Americas' Security Affairs, Defense Threat Reduction Agency (DTRA), and several national laboratories (Los Alamos National Laboratory, Oak Ridge National Laboratory, Savannah River National Laboratory, Sandia National Laboratory, and Pacific Northwest National Laboratory).

1.2 Scope

This standard supplements the performance requirements for radionuclide detection and identification for selected industrial and special nuclear materials (SNM), both bare and shielded, and expands the performance requirements for detection and identification of SNM under conditions of masking by industrial, medical, or NORM sources. Radiation detection and identification performance requirements for other radionuclides, as well as mechanical, environmental and electromagnetic performance requirements for Hand-Held Radioisotope Identification Devices (RIID) are included in ANSI/IEEE N42.34.

This TCS addresses the mandate in the SAFE Port Act (H.R. 4954–16, Subtitle C—Port Operations, Section 121(f) Standards) [7] that states: "The Secretary, acting through the Director for Domestic Nuclear Detection and in collaboration with the National Institute of Standards and Technology, shall publish technical capability standards and recommended standard operating procedures for the use of nonintrusive imaging and radiation detection equipment in the United States.

Such standards and procedures:

1. Should take into account relevant standards and procedures utilized by other Federal departments or agencies as well as those developed by international bodies; and

2. Shall not be designed so as to endorse specific companies or create sovereignty conflicts with participating countries."

1.3 Purpose

The purpose of this standard is to establish the technical performance requirements for the detection and identification of specific SNM and shielded radioactive sources by hand-held instruments with radionuclide identification capabilities as a supplement to the ANSI N42.34 standard. This standard will be used by DNDO to test equipment performance via, for example, the Graduated Rad/Nuc Detector Evaluation and Reporting (GRaDER^{SM}) program [12].

2 References

The following documents are referenced in this TCS. If a reference does not have a date, then the most recent version applies.

[1] ANSI/IEEE N42.34 American National Standard - American National Standard Performance Criteria for Hand-held Instruments for the Detection and Identification of Radionuclides.

[2] International Atomic Energy Agency (IAEA), "Categorization of Radioactive Sources" Safety Guide No RS-G-1.9 (2005).

[3] U.S. Department of Homeland Security, Domestic Nuclear Detection Office, Document Number 200-DNDO-107500v2.00, "DNDO Scoring Criteria."

[4] U.S. Department of Homeland Security, Domestic Nuclear Detection Office, INTERIM SECURITY CLASSIFICATION GUIDE, DHS Interim SCG DNDO-001 (General), April 3, 2009.

[5] ANSI/IEEE N42.42 American National Standard - Data format standard for radiation detectors used for Homeland Security.

[6] ANSI/HPS N13.11, "Criteria for Testing Personnel Dosimetry Performance."

[7] SAFE Port Act, H.R. 4954, One Hundred Ninth Congress of the United States of America, at second session 2006.

[8] ISO 4037-3, X and gamma reference radiation for calibrating dosimeters and dose rate meters and for determining their 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.

[9] ANSI/IEEE N42.22, American National Standard - traceability of radioactive sources to the National Institute of Standards and Technology (NIST) and Associated Instrument Quality Control.

[10] ANSI/IEEE N42.23, American National Standard measurement and associated instrument quality assurance for radio assay laboratories.

[11] Soares, C. G. and P. R. Martin, "A Consistent Set of Conversion Coefficients for Personnel and Environmental Dosimetry", Proceedings of the Panasonic User's Group Meeting, Somerset, PA, June 5-9, 1995.

[12] Information on GRaDER program can be obtained from http://www.dhs.gov/files/programs/gc_1218637329931.shtm.

[13] Fundamental quantities and units for ionizing radiation. Journal of the International Commission on Radiation Units and Measurements - ICRU Report 60.

[14] ANSI/IEEE N42.14, American National Standard for Calibration and Use of Germanium Spectrometers for the Measurement of Gamma-Ray Emission Rates of Radionuclides.

[15] LANL Report LA-5681, Portal Monitor for Diversion Safeguards, 1974.

3 Definitions and Abbreviations

3.1 Definitions

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

Exposure: A measure of ionization produced in air by X- or gamma-ray radiation. The special unit of exposure rate is the roentgen per hour, abbreviated in this standard as R/h.

False negative: A lack of indication by the instrument to a radioactive source that is present.

False positive: An indication by the instrument that a radioactive source is present when the source is not present.

Fluence: The *fluence*, Φ, is the quotient of dN *by* da, where dN is the number of particles incident on a sphere of cross-sectional area da. The unit of fluence is m^{-2}. (ICRU Report 60 [13])

Fluence rate: The *fluence rate,* $\dot{\Phi}$, is the quotient of dΦ by dt, where dΦ is the increment of the fluence in the time interval dt, thus $\dot{\Phi} = \frac{d\phi}{dt}$. The unit of fluence rate is $m^{-2}s^{-1}$. (ICRU Report 60 [13])

Influence quantity: Quantity that may have a bearing on 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.

Masking ratio: Exposure rate or count rate of confounding sources compared to exposure rate or count rate of target source.

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

Precision: Degree of agreement of repeated measurements of the same parameter.

Reference point of an instrument: Physical mark, or marks, on the outside of an instrument used to position it at a point where the conventionally true value of a quantity is to be measured, unless the position is clearly identifiable from the construction of the instrument.

Special nuclear material (SNM): The term "special nuclear material" refers to:

1. Plutonium, Uranium–233, Uranium enriched in the isotope 233 or in the isotope 235, and any other material that the Commission, pursuant to the provisions of section 51 of the Act, determines to be special nuclear material, but does not include source material;

2. Any material artificially enriched by any of the foregoing but does not include source material.

Standard test conditions: The range of values of a set of influence quantities under which a calibration or a measurement of response is carried out.

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

Uncertainty: Parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

NOTES

1. The parameter may be, for example, a standard deviation (or a given multiple of it), of the half width of an interval having a stated level of confidence.
2. Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results from a series of measurements and can be characterized by experimental standard deviations. Other components, which also can be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.
3. It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion of values.

3.2 Abbreviations and Acronyms

AAR	Additional Allowed Radionuclides
ANSI	American National Standards Institute
CBP	Customs and Border Protection
CONEX	Container Express
DHS	Department of Homeland Security
DNDO	Domestic Nuclear Detection Office
DOE	Department of Energy
DOT	Department of Transportation

DTRA	Defense Threat Reduction Agency
DU	Depleted Uranium
ENSDF	Evaluated Nuclear Structure Data File
FBI	Federal Bureau of Investigation
FWHM	Full Width Half Maximum
GRaDER[SM]	Graduated Rad/Nuc Detector Evaluation and Reporting
HDPE	High-Density Polyethylene
HEU	Highly Enriched Uranium
HPGe	High-Purity Germanium
HPS	Health Physics Society
IAEA	International Atomic Energy Agency
ICRU	International Commission on Radiation Units and Measurement
IEEE	Institute of Electrical and Electronics Engineers
LANL	Los Alamos National Laboratory
NIST	National Institute of Standards and Technology
NORM	Naturally Occurring Radioactive Material
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PMMA	Polymethyl Methacrylate
PNNL	Pacific Northwest National Laboratory
POV	Privately Owned Vehicle
RIID	Radioisotope Identification Devices
RR	Required Radionuclide
SNM	Special Nuclear Material
SRNL	Savannah River National Laboratory
TCS	Technical Capability Standard
TCSWG	Technical Capability Standard Working Group
WGPu	Weapons Grade Plutonium

4 General Considerations

4.1 Test Conditions

Except where otherwise specified, the tests in this standard shall be carried out under the standard test conditions shown in Table 1.

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	20% to 75%
Atmospheric pressure	70 to 106.6 kPa (525 to 800 mm Hg at 0° C)
Angle of incidence of radiation	Direction given ± 5° perpendicular from the surface of the detector (normal direction)
Magnetic induction of external origin	Less than twice the value of the induction due to Earth's magnetic field
Instrument controls	As defined by the manufacturer
Gamma Background Radiation (ambient photon exposure rate)	≤ 20 μR/h
Neutron Background Radiation	≤ 600 neutrons per second per meter^2

4.2 Units and Uncertainties

4.2.1 Uncertainties

Unless otherwise specified, the uncertainties for any measurable quantity (e.g. radiation field), shall be documented and should not exceed 5% with a coverage factor (k) of 1.

4.2.2 Units

This standard uses the International System of Units (SI). Multiples and submultiples of SI units will be used, when practicable, according to the SI system.

This standard also uses the following non-SI units:

Energy: Kilo-electron-volt (keV), 1 keV = 1.602×10^{-16} J, and mega-electron-volt (symbol: MeV), 1 MeV = 1.602×10^{-13} J

Exposure: Roentgen (R), 1 R = 2.58×10^{-4} C/kg.

Exposure rate: Roentgen per hour (R/h), 1 R/h = 2.58×10^{-4} C/kg/h.

4.2.3 Conversion Coefficients (Information Only)

Exposure rate can be converted to air-kerma rate by using the conversion equations for air listed in Table 2.

Table 2. Roentgen to Gy Conversion Equations for Air

Radionuclide	Conversion Equation
Photons (<300 keV)	1 R/h = 8.764 mGy/h
^{137}Cs	1 R/h = 8.778 mGy/h
^{60}Co	1 R/h = 8.792 mGy/h

For X-rays and gamma rays, the factor to convert from absorbed-dose (Gy) to dose equivalent (Sv) is equal to 1. Therefore, in SI units 1 Gy = 1 Sv.

Conversion coefficients can be used to convert from air-kerma to dose equivalent quantities such as the deep and shallow ambient dose equivalent *(H*(10)* and *H*(0.07)*), and the deep and shallow personal dose equivalent *(Hp(10)* and *Hp(0.07)*). The conversion coefficients are tabulated as a function of photon energy for ISO beam qualities in ISO 4037:3.

A subset of conversion coefficients from air-kerma to deep ambient dose equivalent, *H*(10)*, (International Commission on Radiation Units and Measurement (ICRU) Tissue Sphere Phantom at a depth of 10 mm) is given in Table 3.

Table 3. Conversion Coefficients from Air-Kerma to *H*(10)*

Photon Source C_k	Sv/Gy*	C_x (rem/R)
^{241}Am	1.74	1.66
N^{80} (65 keV)	1.73	1.65
^{137}Cs	1.20	1.06
^{60}Co	1.16	1.03
* ISO 4037:3		

4.3 Special Word Usage

The following word usage applies:

- "Shall" signifies a mandatory requirement (where appropriate a qualifying statement is included to indicate that there may be an allowable exception).
- "Should" signifies a recommended specification or method.
- "May" signifies an acceptable method or an example of good practice.

5 General Characteristics

5.1 General

Instruments addressed by this standard are used for the detection and identification of radionuclides; detection of neutron radiation is optional and neutron detection requirements are not addressed in this standard.

These instruments typically acquire the gamma-ray spectrum and identify the radionuclide through comparison with an internal radionuclide library. Instruments tested under this standard have a detection mode that can be used to measure exposure, count or dose rates to localize a radioactive source before performing a long-dwell measurement of the gamma-ray spectrum.

These instruments shall be capable of downloading data to an external location.

5.2 Instrument Categories by Usage

Instruments can be categorized depending on their usage in specific scenarios. These categories are commonly described as:

- **Containerized cargo**: screening of trucks, trains, shipping containers (CONEX), large ships, large planes (e.g., objects whose weight generally exceeds 2,000 kg.)
- **Conveyances**: screening of POV, small boats, small aircraft (e.g., objects whose weight generally falls between 50 and 2,000 kg.)
- **Pedestrians/Packages**: screening of people, small areas, animals, luggage, mail (e.g., objects whose weight is generally less than 50 kg.)

For the purposes of this standard only, these last two categories are combined. That is, the two categories in this TCS are referred to as containerized cargo and conveyances/pedestrians.

All instruments, independent of category, shall meet all of the requirements of this standard with the one difference as indicated in Section 6.1.

NOTE

Successful completion of the radiation tests described in this standard should not be construed as an ability to successfully detect or identify gamma radiation in all environments.

5.3 Instrument Functional Modes

The instrument shall, as a minimum, have the following two functional modes:

Identification mode: displays the identification of the radionuclides present during a measurement.

Detection mode: displays a measurement of source intensity such as count rate, exposure rate or dose rate. This mode can be used for detecting and locating a radioactive source. An alarm indication shall be provided for detection of an increase in the radiation field intensity. The alarm threshold and alarm on/off function shall be user settable. This mode may provide dynamic radionuclide identification.

The performance requirements and testing methods for each functional mode are described in Section 6.

5.4 Testing Parameter Requirements

The testing parameters depend on the instrument functional modes. The following parameters shall be used unless otherwise specified in a particular test:

1. **For detection mode**: measurement speed shall be 0.5 m/s (average human walking speed) for all instrument categories. A detection is defined as an alarm. Alarm thresholds are set based on ANSI/IEEE N42.34 to meet the false alarm rate requirements.

2. **For identification mode**: measurement time depends on the instrument category as specified per Section 5.2 of this standard.

   - For the Containerized cargo category the measurement time shall be 300 seconds.
   - For the Conveyances/Pedestrians category the measurement time shall be 60 seconds.
   - All RIIDs, irrespective of their category of usage, shall meet a minimum set of performance requirements per Section 6. As described in Section 5.10.3 and Section 6.1, differing test sources and test parameters are used to comply with the performance requirements for the Containerized cargo category.

5.5 Scoring and Measurement Requirements

5.5.1 Test Replication

All tests shall be replicated 10 times.

5.5.2 Compliance with the Requirement

For each test and for each source, an instrument complies with a requirement if no more than two failures in 10 trials are observed.

5.5.3 Test Scoring

Tests for radionuclide identification of target sources shall be scored using Categories C3 and C4 from the DNDO technical scoring criteria [3].

Tests for radionuclide identification of masking sources (no target sources present, 6.3) shall be scored using Table 14 in Appendix A from the DNDO technical scoring criteria [3].

The appropriate instrument response depends on the type of target source measured. The response is correct when the instrument identifies all of the main radionuclides present in the target source. The reporting of additional acceptable radionuclides and background radionuclides

-is sometimes allowed. Appendix A details the DNDO scoring criteria as it applies to this standard.

Test Scoring: Exception for High Masking Ratio Test Cases

An exception is allowed for masking ratios greater than 5:1. If the instrument is unable to identify the presence of HEU or WGPu at the fluence rates for the masking sources defined in Table 8, Table 9 and Table 10 due to excessive count rates (at the energy region of interest for HEU and WGPu), then the instrument shall provide a message indicating that it cannot identify HEU, WGPu or both.

For tests involving masking ratios of 5:1 or smaller, the instrument response shall be considered incorrect if the masking radionuclide is identified without the identification of the main radionuclide of interest.

5.6 Test Reporting

All radionuclides displayed by the instrument shall be recorded by the tester. All spectra acquired from a test shall be saved and associated with the instrument response displayed for that test.

5.7 Laboratory Test Equipment

The testing laboratory shall be equipped with a calibrated High-Purity Germanium (HPGe) detector. This HPGe detector shall be used for:

1. Checking for gamma-ray emitting impurities that could be present in the sources to be used for the tests; the impurity measurements will be used to update the list of Additional Allowed Radionuclides (AAR) in Table 14.
2. Determining the fluence rates, which may be used to determine masking ratios and shielding thicknesses,
3. For measuring the radiation background at the testing location to adjust the fluence rates of the sources used during testing. The energy response of the HPGe detector shall be measured prior to performing these radiation background measurements (see reference [14]). The radiation background calculation shall be computed within an energy range from 100 keV to 3 MeV. Note that a calibrated ionization chamber type instrument, with a known uniform energy response between 100 keV to 3 MeV, may be used for the determination of the radiation background.

Sources used for calibration of HPGe detectors shall be NIST traceable and shall cover an energy range no smaller than 60 keV to 2.6 MeV. The calibration shall be performed as described in ANSI/IEEE N42.14 [14]. Information about calculating fluence rate is provided in Appendix B.

5.8 Source-to-Detector Distance During Measurements

Sources shall be placed at a distance between 50 cm and 1.5 m from the point where the reference point of the instrument is located during the measurements.

5.9 Radiation Background Considerations at Test Location

The fluence rates in the tables listed under Section 5.10 are determined for a 20 μR/h radiation background level. If testing is performed at a different location with a lower radiation background level, the fluence rate shall be scaled by the square root of the ratio of the background to 20 μR/h. See Appendix B.3 for an example.

5.10 Source Configuration Requirements

5.10.1 ^{241}Am Emissions in WGPu Sources

The amount of ^{241}Am varies widely for different WGPu sources. There is a need to limit the amount of low-energy gamma-ray emissions from ^{241}Am to ensure that test results (mainly instrument response) are comparable when tests are performed using different WGPu sources.

For WGPu sources the net count rate of the 60 keV line from ^{241}Am shall be no more than 10 times greater than that of the net count rate of the 414 keV line for ^{239}Pu (e.g., if the count rate for ^{239}Pu is 100 cps then the count rate for the 60 keV line for ^{241}Am shall not exceed 1,000 cps). Copper shall be used as the shielding material to reduce these low-energy emissions (copper alloy ASTM B152).

5.10.2 Shielded Industrial Sources

Shielded industrial sources used in this standard are in part based on International Atomic Energy Agency Categories 2 and 3. These sources are typically encountered while shielded for transport. The source configurations used for testing allows the tester to select from a range of source activities and shielding materials (Table 4).

When using steel as the shielding material, the thickness of the shielding shall be greater than 5 mm. If lead is used, there is no minimum thickness requirement. The radioactive source shall be completely surrounded by the shielding.

For the source configurations in Table 4, the fluence rate was calculated based on assuming that:

- Sources are transported as Department of Transportation (DOT) Yellow II packages (for a maximum exposure rate of 1 mR/h at distance of 1 m)
- Measurements are performed at a distance of 1.5 m. The calculations use a cutoff energy of 40 keV.

For the detection part of the test there is going to be an additional contribution from the DU shielding to the fluence rate stated in Table 4.

Table 4. Shielded Industrial Sources—All Instrument Categories

Radionuclide	Activity Range*	Fluence Rate at Testing Point (photons/s/cm^2)§†	Shielding Material
^{60}Co	0.8–8 Ci	100 ± 10%	Steel or lead or DU¶ or a combination of these materials
^{137}Cs	3–30 Ci	320 ± 10%	Steel or lead or DU¶ or a combination of these materials
^{192}Ir	200–20 Ci	240 ± 10%	Steel or lead or DU¶ or a combination of these materials

* These values were provided by the NRC
§ Uncertainties have a coverage factor, k, of 1.
† Fluence rates correspond to a radiation background level of 20 μR/h
¶ DU as used in shipping containers

5.10.3 Bare and Shielded Sources

The HEU, WGPu and DU sources used for the bare and shielded test cases shall conform to those listed in Table 5 for instruments categorized for Conveyances/Pedestrians, Table 6 for instruments categorized for Container cargo, and Table 7 (^{237}Np only) for instruments in both categories. The fluence rate is based on using the 186 keV gamma-ray line for HEU, the 414 keV gamma-ray line for WGPu, and the 1001 keV gamma-ray line for DU. For each source configuration listed in Table 5, Table 6, and Table 7, take a spectrum using a characterized HPGe detector and measure the fluence rate at the point where the reference point of the instrument is going to be located during the measurements. Sources may be unshielded or may be shielded with steel or high density polyethylene (HDPE). When using steel as the shielding material, the thickness of the shielding shall be greater than 5 mm. When using HDPE, the thickness of the shielding shall be greater than 4 cm.

Table 5. HEU, WGPU and DU Shielded and Bare Sources—Conveyances/Pedestrians Category

Source	Shielding Material	Minimum Source Thickness (mm)*	Fluence Rate At Testing Point (photons/s/cm^2)§†
HEU	None	1	0.68 ± 10%
HEU	Steel	1	0.68 ± 10%
HEU	HDPE	1	0.68 ± 10%
WGPu	None	5	1.1 ± 10%
WGPu	Steel	5	1.1 ± 10%
WGPu	HDPE	5	1.1 ± 10%
DU	None	3	0.22 ± 10%
DU	Steel	3	0.22 ± 10%
DU	HDPE	3	0.22 ± 10%

§ Uncertainties have a coverage factor, k, of 1.
* Thickness are based in the 95% of infinite thickness emission rate, see Reference 15. The DU thickness is based on commonly available standard reference materials.
† Fluence rates correspond to a radiation background level of 20 μR/h

Table 6. DU, HEU and WGPU Shielded and Bare Sources—Containerized Cargo Category

Source	Shielding Material	Minimum Source Thickness (mm)§	Fluence Rate at Testing Point (photons/s/cm^2)*†
HEU	None	1	1.6 ± 10%
HEU	None	1	0.18 ± 10%
HEU	Steel	1	0.18 ± 10%
HEU	HDPE	1	0.18 ± 10%
WGPu	None	5	3.8 ± 10%
WGPu	None	5	0.30 ± 10%
WGPu	Steel	5	0.30 ± 10%
WGPu	HDPE	5	0.30 ± 10%

* Uncertainties have a coverage factor, k, of 1.
§ Thickness are based in the 95% of infinite thickness emission rate, see Reference 15. The DU thickness is based on commonly available standard reference materials.
† fluence rates correspond to a radiation background level of 20 μR/h

The source configuration in Table 7 shall be used for testing. These test cases include ^{237}Np with no additional shielding or masking.

Table 7. ^{237}Np Test Cases—All Instrument Categories

Target Source	Quantity	Distance (m)	Shielding Material	Shielding Thickness	Masking Source	Masking Ratio
^{237}Np	90 mg	1.5	None	None	None	None

5.10.4 Masking Using Medical Sources

Testing per Section 6 shall be conducted using the source configurations described in Table 8. Measurements of the fluence rate for the target and masking sources shall be performed at the same distance. During actual testing the masking material shall be located near the target source (both sources should be located within the 50 cm to 1.5 m source-to-detector distance defined in Section 5.8), but neither source shall provide additional shielding of the other.

For masking test cases using medical sources, the masking ratios are based on the fluence rate for the following gamma-ray lines: 186 keV for HEU, 414 keV for WGPu, 141 keV for ^{99m}Tc, 185 keV for ^{67}Ga, and 364 keV for ^{131}I. To determine the fluence rate for each source, and subsequently determine masking ratios, place a characterized HPGe detector at a distance from the target source where the reference point of the instrument is going to be located during the measurements. Take a 5-minute spectrum of the target source, obtain the net peak area for the corresponding gamma-ray line and divide this number by the live time. Place the medical source at the same location as the target source, take a 5-minute spectrum, obtain the net peak area for the corresponding gamma-ray line and divide this number by the live time. Use these measured values to determine the different masking ratios. Calculations of masking ratios should be based on background subtracted spectra. Several sources may be required to obtain the different masking ratios listed in Table 8.

Medical sources used in this standard shall be surrounded by 7.5 cm of polymethyl methacrylate (PMMA) to simulate in vivo measurements. This shielding thickness is consistent with the half thickness of the phantom used in the ANSI/HPS N13.11 standard [6].

Table 8. Masking with Medical Sources—All Instrument Categories

Target Source Material	Fluence Rate of Target Source at Testing Point (photons/s/cm^2)*†	Masking Source	Masking Ratios
HEU	0.68 ± 10%	^{99m}Tc	10:1, 5:1
HEU	0.68 ± 10%	^{67}Ga	10:1, 5:1
HEU	0.68 ± 10%	^{131}I	10:1, 5:1
WGPu	1.1 ± 10%	^{99m}Tc	10:1, 5:1
WGPu	1.1 ± 10%	^{67}Ga	10:1, 5:1
WGPu	1.1 ± 10%	^{131}I	10:1, 5:1

* Uncertainties have a coverage factor, k, of 1.
† Fluence rates correspond to a radiation background level of 20 μR/h

5.10.5 Masking Using Industrial Sources

Testing per Section 6 shall be conducted using the source configurations described in Table 9. The fluence rate for the target and masking sources shall be measured at the same distance. During actual testing the masking material shall be located near the target source (both sources should be located within the 50 cm to 1.5 m source-to-detector distance defined in Section 5.8) but neither source shall provide additional shielding of the other.

For masking test cases using industrial sources, the masking ratios are based on the fluence rate for the following gamma-ray lines: 662 keV for ^{137}Cs, 317 keV for ^{192}Ir, 1,332 keV for ^{60}Co, 186 keV for HEU, and 414 keV for WGPu. To determine the fluence rate for each source and masking ratios for each configuration, place a characterized HPGe detector at a distance from the target source where the reference point of the instrument is going to be located during the measurements. Take a 5-minute spectrum of the target source, obtain the net peak area for the corresponding gamma-ray line and divide this number by the live time. Place the industrial source at the same location as the target source, take a 5-minute spectrum, obtain the net peak area for the corresponding gamma-ray line and divide this number by the live time. Use these measured values to determine the different masking ratios. Calculations of masking ratios should be based on background subtracted spectra. Several sources may be required to obtain the different masking ratios listed in Table 9.

Table 9. Masking with Industrial Sources—All Instrument Categories

Target Source Material	Fluence Rate of Target Source at Testing Point (photons/s/cm^2)*†	Masking Source	Masking Ratios
HEU	1.6 ± 10%	^{60}Co	10:1, 5:1
HEU	1.6 ± 10%	^{137}Cs	10:1, 5:1
HEU	1.6 ± 10%	^{192}I	10:1, 5:1
WGPu	3.8 ± 10%	^{60}Co	10:1, 5:1

Target Source Material	Fluence Rate of Target Source at Testing Point (photons/s/cm^2)*†	Masking Source	Masking Ratios
WGPu	3.8 ± 10%	^{137}Cs	10:1, 5:1
WGPu	3.8 ± 10%	^{192}I	10:1, 5:1
* Uncertainties have a coverage factor, k, of 1. † Fluence rates correspond to a radiation background level of 20 μR/h			

5.10.6 Masking Using Simulated NORM Sources

For NORM masking test cases per Section 6, the masking ratios shall be based on a total flux calculation from 65 keV to 3 MeV to prevent the inclusion of the 60 keV gamma-rays from ^{241}Am in the WGPu sources.

The isotopic composition and activity of different NORM materials, such as zircon, monazite and allanite, vary widely from sample to sample. Therefore, point sources are used to ensure greater consistency and traceability in performing the measurements. The simulation of bulk NORM sources by point sources of similar isotopic composition is considered appropriate in this case because all measurements will be conducted in a stationary mode and the relative intensity of the radioactive flux measured by the detector would not vary for either a bulk or point source. In addition, due to the relatively small size of the detector in a handheld device, the radioactive flux incident on the detector material will be essentially constant over the entire surface of the detector.

The simulation of bulk NORM sources shall be done by surrounding ^{226}Ra and ^{232}Th sources with 10 cm of PMMA such that each source produces the same total fluence rate.

To determine the appropriate fluence rate for masking ratios, place a characterized HPGe detector at a distance from the target source such that the fluence rate for the 186 keV line for HEU, the 414 keV line for WGPu, and the 1,001 keV line for DU shall be as specified in Table 10. This distance defines where the reference point of the instrument under test will be located during the actual measurements. Calculations of masking ratios should be based on background subtracted counts, not on measured gross counts. Ensure that there are no sources in the vicinity, take a 5 minute background spectrum at the measurement location. Take a 5-minute spectrum of the target source, subtract the background, integrate the counts from 65 keV to 3 MeV and divide this number by the live time. Place the simulated NORM at the same location as the target source, take a 5-minute spectrum, subtract the background, integrate the counts from 65 keV to 3 MeV and divide this number by the live time. Use background subtracted values to determine the different masking ratios listed in Table 10. Several shielded ^{226}Ra and ^{232}Th sources may be required to obtain the different masking ratios. During actual testing the masking material shall be located near the target source (both sources should be located within the 50 cm to 1.5 m source-to-detector distance defined in Section 5.8), but neither source shall provide additional shielding of the other.

Table 10. Masking with NORM Sources—All Instrument Categories

Target Source Material	Fluence Rate of Target Source at Testing Point (photons/s/cm^2)*†	Masking Source	Masking Ratios
HEU	1.6 ± 10%	Simulated NORM	10:1, 5:1
WGPu	3.8 ± 10%	Simulated NORM	10:1, 5:1
DU	3.9 ± 10%	Simulated NORM	10:1, 5:1
* Uncertainties have a coverage factor, k, of 1. † Fluence rates correspond to a radiation background level of 20 μR/h			

5.10.7 Isotopic Composition of Sources

The isotopic composition for the SNM and DU sources shall meet the following conditions:

- HEU shall have at least 90% ^{235}U and no more than 250 ppt ^{232}U
- DU shall have no more than 0.4% ^{235}U
- WGPu shall have no more than 6.5% ^{240P}U and no less than 93% ^{239}Pu.

6 Radiological Tests

6.1 Single Radionuclide Detection and Identification—No Masking

6.1.1 Requirements

Detection mode: All instruments, irrespective of category of usage, shall detect the bare and shielded target source test cases listed in Table 4, Table 5 and Table 7, based on the testing parameters in Section 5.4.

Identification mode: All instruments shall correctly identify the sources listed in Table 4, Table 5, and Table 7 using the measurement times listed in Table 11.

Instruments meeting the Container cargo category shall in addition correctly identify the sources listed in Table 6 using the measurement time listed in Table 11.

Table 11. Measurement Times for Listed Test Cases

Test Cases	Instrument Category	Measurement Time (seconds)
Table 4	All	60
Table 5	Conveyances/Pedestrians	60
Table 6	Containerized cargo	300
Table 7	All	300

6.1.2 Test Method

Detection mode: For each test trial, the bare and shielded target sources in Table 4, Table 5 and Table 7 shall be moved past the instrument per the testing parameters in Section 5.4. The instrument performance complies with the TCS requirements if the instrument detects the radionuclides 8 of 10 times per Section 5.5.1. Before the next trial, ensure that the instrument background has been refreshed per manufacturer's instructions, if appropriate.

Identification mode: For each test trial, the instrument shall be exposed to the bare and shielded target sources in Table 4, Table 5 and Table 7 per the testing parameters in Section 5.4 and Table 11. The instrument performance complies with the TCS requirements if the instrument correctly identifies the radionuclides 8 of 10 times, per Section 5.5.1. Before the next trial, ensure that the instrument background has been refreshed per manufacturer's instructions, if appropriate.

This test shall be repeated with the sources listed in Table 6 for the Container cargo category.

6.2 Simultaneous Radionuclide Identification—Masking

6.2.1 Requirements

The instrument shall identify the target sources in Table 8, Table 9, and Table 10 for the masking test cases using the measurement times listed in Table 12.

Table 12. List of Tests for Masked Sources for All Instrument Categories

Test Cases	Instrument Category	Measurement Time (seconds)
Table 8	All	60
Table 9	All	300
Table 10	All	300

6.2.2 Test Method

For each test trial, the instrument shall be exposed to the masked target sources in Table 8, Table 9 and Table 10 using the measurement times listed in Table 12. The instrument performance complies with the TCS requirements if the instrument correctly identifies the radionuclides 8 out of 10 times per Section 5.5.1. Prior to the next trial, ensure that the instrument background has been refreshed per manufacturer's instructions, if appropriate.

6.3 False-Positive Identifications Produced By Masking Radionuclides

6.3.1 Requirement

The instrument shall correctly identify the masking sources in Tables 8 to 10 (i.e., simulated NORM (^{226}Ra and ^{232}Th), ^{60}Co, ^{137}Cs, ^{192}Ir, ^{67}Ga, ^{99m}Tc, and ^{131}I) in the tested configuration corresponding to a masking ratio of 5:1 per the testing parameters in Section 5.4 and Table 12 when no target source is present.

6.3.2 Test Method

For each test trial, the instrument shall be exposed to the masking sources in Table 8, Table 9 and Table 10 in the tested configuration corresponding to a masking ratio of 5:1 using the measurement times listed in Table 12. The instrument performance complies with TCS requirements if the instrument correctly identifies the masking radionuclides 8 of 10 times per Section 5.5.1 without producing any false positive responses in 10 of 10 times. Prior to the next trial, ensure that the instrument background has been refreshed per manufacturer's instructions, if appropriate.

7 Documentation

7.1 Certificate

A certificate shall accompany each hand-held radionuclide identification instrument, giving at least the following information:

1. Manufacturer's name or registered trademark
2. Type of the instrument and serial number
3. Exposure rate range
4. Energy range
5. FWHM and efficiency for the required radionuclides per ANSI N42.34
6. Results from standard ANSI/IEEE N42.34 testing and the list of radionuclides to which the instrument was tested.

7.2 Operation and Maintenance Manual

Each instrument shall be supplied with operating instructions and maintenance and technical documentation.

Appendix A: Scoring Definitions

Scoring is based on the DNDO scoring criteria listed in Reference 3. For the purpose of this standard, the alarm scoring logic listed in Table 13 shall be used. This scoring logic is a strict technical scoring; operational scoring criteria may differ.

Table 13. Detection Alarm Scoring Logic

Source	Detection System Alarm Response			
	Gamma Only	Neutron Only	Gamma & Neutron	None
Simulated NORM	Correct	False Positive	False Positive	False Negative
^{137}Cs	Correct	False Positive	False Positive	False Negative
^{60}Co	Correct	False Positive	False Positive	False Negative
^{237}Np	Correct	False Positive	False Positive	False Negative
^{192}Ir	Correct	False Positive	False Positive	False Negative
WGPu	Correct	Correct	Correct	False Negative
DU	Correct	False Positive	False Positive	False Negative
HEU	Correct	False Positive	False Positive	False Negative
^{99m}Tc	Correct	False Positive	False Positive	False Negative
^{131}I	Correct	False Positive	False Positive	False Negative
^{67}Ga	Correct	False Positive	False Positive	False Negative
^{201}Tl	Correct	False Positive	False Positive	False Negative
HEU + ^{60}Co	Correct	False Positive	False Positive	False Negative
HEU + ^{137}Cs	Correct	False Positive	False Positive	False Negative
HEU + ^{192}Ir	Correct	False Positive	False Positive	False Negative
WGPu + ^{60}Co	Correct	Correct	Correct	False Negative
WGPu + ^{137}Cs	Correct	Correct	Correct	False Negative
WGPu + ^{192}Ir	Correct	Correct	Correct	False Negative
HEU + ^{99m}Tc	Correct	False Positive	False Positive	False Negative
HEU + ^{131}I	Correct	False Positive	False Positive	False Negative
HEU + ^{67}Ga	Correct	False Positive	False Positive	False Negative
WGPu + ^{99m}Tc	Correct	Correct	Correct	False Negative
WGPu + ^{131}I	Correct	Correct	Correct	False Negative
WGPu + ^{67}Ga	Correct	Correct	Correct	False Negative
HEU + simulated NORM	Correct	False Positive	False Positive	False Negative
WGPu + simulated NORM	Correct	Correct	Correct	False Negative
DU + Simulated NORM	Correct	False Positive	False Positive	False Negative
No source	False Positive	False Positive	False Positive	Correct

The DNDO technical scoring logic for identification is employed in this analysis. Table 14 provides a summary of the Required Radionuclides (RR) as well as AARs for each test source.

For the purposes of this analysis, correct identification requires that the detection system report the radionuclides that are present (DNDO C3 (Correct 3) and C4 (Correct 4) criteria.

Category C3

The DNDO C3 category requires at least one RR to be identified and allows only AARs and NORM identifications to accompany the RRs; any other identification is considered incorrect.

Category C4

The DNDO C4 criterion requires all RRs to be identified and allows only AARs and NORM identifications to accompany the RRs; any other identification is considered incorrect. In the DNDO technical scoring NORM is not considered a source. Therefore for the test scenario when no source is present providing any NORM radionuclide or No Identification is considered correct (C4).

If the radiation detection systems provide messages that are not radionuclide- specific such as Unknown Source, Extras, Isotope not in library, Bad ID, Source not in library, Not in library, Gross counts, High Gamma, or Detection Compromise; then these messages shall be counted as FP5 (False Positive 5) and FP6 (False Positive 6) as described in the DNDO Scoring Logic document.

Category FP5

The category FP5 means the instrument identified the presence of elevated radiation without identifying any specific radionuclides when at least one RR was in the instrument’s library.

Therefore, to be in this category, there is a target source present. The instrument did not report any radionuclide; it only reported a message, such as “Unknown” or “Bad ID,” and the RRs are in the instrument library.

Category FP6

The category FP6 means the instrument identified the presence of elevated radiation without identifying any specific radionuclides; no RR was in the instrument’s library.

Therefore, to be in this category, there is a target source present. The instrument did not report any radionuclide; it only reported a message, such as “Unknown” or “Bad ID,” and the RRs are not in the instrument library.

Table 14: Radionuclide Identification Reporting Used for Scoring

Source	Required Radionuclide (RR)	Additional Acceptable Radionuclide (AAR)
Simulated NORM	^{232}Th, ^{226}Ra	Thorium, Radium
^{137}Cs	^{137}Cs	None
^{60}Co	^{60}Co	None
^{237}Np	^{237}Np	None
^{192}Ir	^{192}Ir	None
WGPu	^{239}Pu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, Plutonium, Pu, WGPu
DU	^{238}U	^{235}U, ^{234m}Pa, Uranium, DU
HEU	^{235}U	^{238}U, ^{234m}Pa, HEU, Uranium
^{99m}Tc	^{99m}Tc	^{99}Mo
^{131}I	^{131}I	None
^{67}Ga	^{67}Ga	None
^{201}Tl	^{201}Tl	^{202}Tl
HEU + ^{60}Co	^{235}U	^{238}U, ^{234m}Pa, HEU, Uranium, ^{60}Co
HEU + ^{137}Cs	^{235}U	^{238}U, ^{234m}Pa, HEU, Uranium, ^{137}Cs
HEU + ^{192}Ir	^{235}U	^{238}U, ^{234m}Pa, HEU, Uranium, ^{192}Ir
HEU + ^{99m}Tc	^{235}U	^{238}U, ^{234m}Pa, ^{99}Mo, ^{99m}Tc, HEU, Uranium
HEU + ^{131}I	^{235}U	^{238}U, ^{234m}Pa, ^{131}I, HEU, Uranium
HEU + ^{67}Ga	^{235}U	^{238}U, ^{234m}Pa, ^{67}Ga, HEU, Uranium
HEU + Simulated NORM	^{235}U	^{232}Th, ^{226}Ra, ^{238}U, ^{234}mPa, HEU, Uranium, Thorium, Radium
WGPu + ^{60}Co	^{239}Pu	^{241}PU, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, Plutonium, Pu, WGPu, ^{60}Co
WGPu + ^{137}Cs	^{239}Pu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, Plutonium, Pu, WGPu, ^{137}Cs
WGPu + ^{192}Ir	^{239}Pu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, Plutonium, Pu, WGPu, ^{192}Ir
WGPu + ^{99m}Tc	^{239}Pu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, ^{99}Mo, ^{99m}Tc, Plutonium, Pu, WGPu
WGPu + ^{131}I	^{239}Pu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, ^{131}I, Plutonium, Pu, WGPu
WGPu + ^{67}Ga	^{239}Pu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, ^{67}Ga, Plutonium, Pu, WGPu
WGPu + Simulated NORM	^{239}Pu	^{232}Th, ^{226}Ra, ^{238}U, ^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, Plutonium, Pu, WGPu, Thorium, Radium
DU + Simulated NORM	^{238}U	^{235}U, ^{234m}Pa, Uranium, DU, ^{232}Th, ^{226}Ra, Thorium, Radium
No Source	None	None

For shielded sources that contain depleted uranium (DU) as part of the shielding, Table 15 provides a summary of the Required Radionuclides (RR) as well as AARs for each test source.

Table 15. Radionuclide Identification Reporting Used for Scoring for Sources Shielded with DU

Source	Required Radionuclide (RR)	Additional Acceptable Radionuclide (AAR)
^{137}Cs	^{137}Cs	^{238}U, ^{235}U, ^{234m}Pa, Uranium, DU
^{60}Co	^{60}Co	^{238}U, ^{235}U, ^{234m}Pa, Uranium, DU
^{192}Ir	^{192}Ir	^{238}U, ^{235}U, ^{234m}Pa, Uranium, DU

Appendix B: Informative Calculations

B.1 Estimates of Exposure Rates

To determine the exposure rate produced by shielded source the following approximation can be used. Other software packages are available but care should be taken with the conversion factors and the mass attenuation coefficients and the mass energy-absorption coefficient used as there are many discrepancies in the literature.

The exposure rate constant expressed in units of R m^2 h^{-1} Ci^{-1} for an isotope that emits one photon of energy hν per disintegration can be approximated as [Ref. B1.2]:

$$\Gamma = 194.5\ h\nu\ (\mu_{ab}/\rho)_{\text{air}}$$

Where h_ν is the energy of the photon emitted expressed in MeV and $(\mu_{ab}/\rho)_{air}$ is the energy absorption coefficient for air expressed in m^2/kg.

The exposure rate constant for an isotope that emits photons $h\nu_1$, $h\nu_2$, $h\nu_3 \ldots h\nu_n$ and the number of these per disintegration is N_1, N_2, $N_3 \ldots N_n$ can be approximated as:

$$\Gamma = 194.5 \sum_{i=1}^{n} N_i\, h\nu_i \left(\frac{\mu_{ab}^i}{\rho}\right)_{air}$$

The exposure rate $\dot{X}$ at any point P, distance *d*, from a source activity (point source) is expressed as:

$$\dot{X} = \frac{\Gamma\, A}{d^2}$$

Then the source activity can be estimated as:

$$A = \frac{\dot{X}\, d^2}{\Gamma}$$

For monoenergetic photons with an incident intensity I_0, penetrating a layer of material with thickness, x (expressed in cm) and density ρ (expressed in g/cm^3), emerges with intensity I given by the exponential attenuation law:

$$\frac{I}{I_0} = \exp\left[-\left({}^{\mu}/_{\rho}\right) x\, \rho\right]$$

Where μ/ρ is the mass attenuation coefficient expressed in units of cm^2/g [Ref. B1.1].

Then for a shielded source the source activity can be approximated as:

$$A = \frac{\dot{X}\, d^2}{194.5\ \sum_{i=1}^{n} N_i\, h\nu_i \left(\frac{\mu_{ab}^i}{\rho}\right)_{air} \exp\left[-\left({}^{\mu}/_{\rho}\right)_i x\, \rho\right]}$$

B.2 References

1. Tables of X-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 MeV for elements Z = 1 to 92 and 48 additional substances of dosimetric interest. NISTIR 5632. J.H. Hubbell and S.M. Seltzer, May 2005. (http://www.nist.gov/pml/data/xraycoef/index.cfm)

2. The Physics of Radiology, 4th Edition, Publisher Charles C. Thomas. Authors: Harold Elford Johns and John Robert Cunningham.

B.3 Summary of Fluence Rate Calculations

Radiation from an X-ray generator or a radioactive source consists of a beam of photons, usually with a variety of energies. If we consider that the beam is monoenergetic, then one way to describe the beam would be to specify the number of photons, dN, that would cross an area, da, taken at right angles to the beam. The ratio of these would yield what the International Commission of Radiological Units and Measurements (ICRU) has called fluence or photon fluence represented by the capital Greek letter phi.

$$\Phi = \frac{\mathrm{dN}}{\mathrm{da}} \qquad (1)$$

At time, one may be interested in the number of photons that pass through unit area per unit time. This is called the fluence rate and it is represented by the lower case Greek letter phi, thus:

$$\phi = \frac{d\Phi}{dt} = \frac{dN}{da\,dt} \qquad (2)$$

When the emission of the source is isotropic and we integrate equation (2), we have that the fluence rate at a radius, *r*, from the source can be expressed as:

$$\phi = \frac{R}{4\pi r^2} \qquad (3)$$

Where *R* is the number of photons per second emitted from the source.

R can be express as a function of the source activity, *A* (expressed in Becquerel), as:

$$R = A * p(E) \qquad (4)$$

Where *p(E)* is the emission probability of a gamma ray at energy E. Then the fluence rate can be expressed as:

$$\phi = \frac{A * p(E)}{4\pi r^2} \qquad (5)$$

If the source emits gamma rays at different energies, then the fluence rate can be expressed as:

$$\phi = \frac{A}{4\pi r^2} \sum_i p(E_i) \qquad (6)$$

Note that the fluence rate value obtained using equation (6) will depend on the cutoff energy used in the calculation. Most radiation detection instruments have difficulties detecting gamma rays with energies lower than 30 keV.

The emission probabilities listed in the Evaluated Nuclear Structure Data File (ENSDF) shall be used for these calculations. These data can be obtained from: http://www.nndc.bnl.gov/.

If the required data are not available in ENSDF a list of the photo peaks and emission probabilities used in the calculation shall be provided as part of the support documentation.

The fluence rate for a single gamma-ray line of energy, *E*, can be measured using a gamma-ray spectrometer equipped with a HPGe or NaI(Tl) detector. In this case the fluence rate can be expressed as:

$$\phi = \frac{Area_{net} * \epsilon(E)}{T_{live} * 4\pi r^2} \qquad (7)$$

where $Area_{net}$ is the net photo-peak area of the gamma line of energy *E*, *(E)* is the detector full-energy peak efficiency for the gamma ray of energy *E*, and T_{live} is the live time of the measurement (expressed in seconds) [Ref. B2.1].

Examples of fluence rate calculations for HEU and WGPu are shown in the tables below.

Table 15. Fluence Rate Calculations for 186 keV Gamma Line of HEU

Mass (g)	Photons per Second	Distance (cm)	Fluence Rate (photons/s/cm^2)	Time (seconds)	Fluence (photons/cm^2)
1,000	4.624E+05	150	1.635E+00	300	4.906E+02
35	4.942E+04	150	1.748E-01	300	5.244E+01
35	4.942E+04	100	3.933E-01	180	7.079E+01
10	2.141E+04	50	6.815E-01	60	4.089E+01
10	2.141E+04	50	6.815E-01	120	8.178E+01

Table 16. Fluence Rate Calculations for 414 keV Gamma Line of WGPu

Mass (g)	Photons per Second	Distance (cm)	Fluence Rate (photons/s/cm^2)	Time (seconds)	Fluence (photons/cm^2)
400	1.064E+06	150	3.763E+00	300	1.129E+03
10	8.494E+04	150	3.004E-01	300	9.012E+01
10	8.494E+04	100	6.759E-01	180	1.217E+02
3	3.512E+04	50	1.118E+00	60	6.707E+01
3	3.512E+04	50	1.118E+00	120	1.341E+02

B.4 References

Gamma- and X-ray Spectrometry with Semiconductor Detectors. K. Debertin and R.G. Helmer. Editor North-Holland. 1998 Edition.

B.5 Example of Fluence Rate Scaling With Radiation Background

The fluence rates in the tables listed under Section 5.10 are determined for a 20 μR/h radiation background level. If testing is performed at a different location with a lower radiation background level, the fluence rate shall be scaled by the square root of the ratio of the background to 20 μR/h.

Table 17. Example of Fluence Rates for Different Radiation Backgrounds

Source	Fluence rate at testing point (photons/s/cm^2) at 20 μR/h	Fluence rate at testing point (photons/s/cm^2) at 10 μR/h	Fluence rate at testing point (photons/s/cm^2) at 5 μR/h
HEU	1.6	1.1	0.8
WGPu	3.8	2.7	1.9

B.6 Full-Energy-Peak Efficiency Calculations

The full-energy-peak efficiency can be determined from gamma-ray lines in the gamma-ray spectrum by:

$$\epsilon\,(E) = \frac{Net\ peak\ area\ (E)}{Activity\ \times T_{live}\ \times P_{\gamma}(E)}$$

Where the Net peak area is the net gamma-ray peak area of energy E, Activity is the source activity at the time of the measurement, T_{live} is the measurement live time and P is the emission probability of the gamma-ray line of energy E.

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