Technical Capability Standard for Handheld Instruments Used for the Detection and Identification of Radionuclides – 2019

Countering Weapons of Mass Destruction
Doc#: 500-DNDO-117250v2.0

Homeland
Security

Revision: November 2019

THIS PAGE INTENTIONALLY LEFT BLANK

Participants

At the time this document version was published, the Technical Capability Standards Working Group consisted of the following membership:

Leticia Pibida, Chair (NIST)

Organization	Representative
Countering Weapons of Mass Destruction	Don Potter
	Lucy Ooi
	John Blackadar
Customs and Border Protection	Kathy McCormick
	Siraj Khan
	Warren Cluff
	Kevin Chan
	Nicholas Long
	Paul Mason
Defense Threat Reduction Agency	Lyndon Wrighten
Department of Defense	Chad McKee
Department of Homeland Security – Science and Technology	Peter Shebell
John Hopkins University - Advance Physics Laboratory	Linda Moniz
	Robert Feuerbach
Federal Bureau of Investigation	Kevin McLeary
Lawrence Livermore National Laboratory	Radoslav Radev
Los Alamos National Laboratory	Thomas McLean
National Nuclear Security Administration	Luc Murphy
	Michael Sheets
Nuclear Regulatory Commission	Cindy Flannery
National Institute of Standards and Technology	Miles McCord
Oak Ridge National Laboratory	Chris Blessinger
	Christina Forrester
Pacific Northwest National Laboratory	Richard Kouzes
	Marcus Sturges
	Michael Demboski
	Paul Johns
Sandia National Laboratories	Dean Mitchell
Savannah River National Laboratory	Al Goodwyn
	Sean Branney
	Peter Chiaro

THIS PAGE INTENTIONALLY LEFT BLANK

Table of Contents

List of Tables

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

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 inspection systems. The purpose of the TCS is to establish, where practical, requirements and applicable test methods that are based on threat-informed unclassified source materials and test configurations that are not addressed in consensus standards. Threat-informed source materials and configurations are 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 [3].

It is anticipated that after a TCS is developed, the Countering Weapons of Mass Destruction (CWMD) Office will work within the consensus standards arena to ensure that future American National Standards Institute (ANSI) N42 series consensus standards reflect the capabilities described by the TCS benchmarks, where applicable.

Technical Capability Standards are developed by an inter-agency TCSWG. Membership of the TCSWG includes representatives from the Department of Homeland Security's (DHS's) Countering Weapons of Mass Destruction Office (CWMD), U.S. Customs and Border Protection (CBP), and Science and Technology Directorate (S&T); the Department of Commerce's National Institute of Standards and Technology (NIST); the Nuclear Regulatory Commission (NRC); the Department of Justice's (DOJ's) Federal Bureau of Investigation (FBI); the Department of Defense's (DoD's) Defense Threat Reduction Agency (DTRA); and from the Department of Energy's (DOE's) National Nuclear Security Administration (NNSA) Office of Counterterrorism and Counterproliferation (NA-80), the Office of Defense Nuclear Nonproliferation (NA-20), and several DOE national laboratories (Lawrence Livermore National Laboratory [LLNL], Los Alamos National Laboratory [LANL], Oak Ridge National Laboratory [ORNL], Sandia National Laboratories [SNL], Savannah River National Laboratory [SRNL], and Pacific Northwest National Laboratory [PNNL]).

1.2 Scope

This TCS supplements ANSI N42.34, American National Standard Performance Criteria for Hand-Held Instruments for the Detection and Identification of Radionuclides. This TCS is for hand-held radioisotope identification devices (RIIDs). It establishes performance requirements for radionuclide detection and identification of 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 and naturally occurring radioactive material (NORM) sources. Radiation detection and identification performance requirements for other radionuclides, as well as mechanical, environmental, and electromagnetic performance requirements for RIIDs are covered by ANSI N42.34 [1].

This TCS addresses the mandate in the Security and Accountability For Every (SAFE) Port Act (Pub. L 109-347 §121 (f) October 13, 2006, 120 Stat. 1898) 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."

The Secretary of Homeland Security, pursuant to a reorganization under Section 872 of the Homeland Security Act of 2002, as amended, established the Countering Weapons of Mass Destruction (CWMD) Office in December 2017. This reorganization was formally authorized by Congress under the Countering Weapons of Mass Destruction Act of 2018 (Public Law No. 115-387), signed by the President on December 21, 2018 [16]. The Assistant Secretary for CWMD serves as the Director for the Domestic Nuclear Detection Office, which was subsumed into the broader CWMD Office.

1.3 Purpose

The purpose of this TCS is to supplement the radiological performance requirements established in ANSI N42.34 [1]. Specifically, this TCS establishes additional requirements and test methods for the detection and identification of SNM, and shielded radioactive sources not covered in the ANSI N42.34 standard. This standard will be used by CWMD to test equipment performance.

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 N42.34-2015 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, Radiological and Nuclear Smuggling Security Classification Guide, DHS SCG DNDO-001.3, November 2017.

[4] ANSI N42.42-2012 American National Standard - Data format standard for radiation detectors used for Homeland Security.

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

[6] SAFE Port Act, Pub. L. No. 109-347, October 13, 2006, 120 Stat 1884.

[7] 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.

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

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

[10] 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.

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

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

[13] 49 CFR 172.103 Department of Transportation, US DOT regulations, transport and packaging of radioactive and nuclear materials (Types I, II, and III) packages.

[14] Technical Capability Standards Traceability Memo, Document number 500-DNDO-119600.

[15] International Atomic Energy Agency, "Code of Conduct on the Safety and Security of Radioactive Sources," January 2004.

[16] Countering Weapons of Mass Destruction Act of 2018, Public Law No. 115-387, One Hundred Fifteenth Congress of the United States of America, at second session 2018.

3 Definitions and Abbreviations

3.1 Definitions

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

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

3.1.3 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.

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

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

3.1.6 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 [11])

3.1.7 fluence rate: The fluence rate, $\dot{\Phi}$ is the quotient of $d\Phi$ by dt, where $d\Phi$ is the increment of the fluence in the time interval dt. The unit of fluence rate is $m^{-2}s^{-1}$. (ICRU Report 60 [11])

3.1.8 flux: The flux, $\dot{N}$, is the quotient of dN by dt, where dN is the increment of the particle number in the time interval dt. The unit of flux is s^{-1}. (ICRU Report 60 [11])

3.1.9 influence quantity: Quantity that may have a bearing on the result of a measurement without being the subject of the measurement.

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

3.1.11 kerma: The kerma, K, is the quotient of dE_{tr} by dm, where dE_{tr} is the sum of the initial kinetic energy of all the charged particles liberated by uncharged particles in a mass dm of material. The unit of kerma is J kg^{-1} or gray (Gy).

3.1.12 masking ratio: Radiation emission rate of the masking source(s) compared to the emission rate of the target source.

3.1.13 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.

3.1.14 special nuclear material (SNM): The term "special nuclear material" means plutonium, uranium enriched in the isotope 233 or the isotope 235, but does not include uranium, thorium, or any other material that is determined by the NRC pursuant to the provisions of Section 61 of the Atomic Energy Act of 1954, as amended, to be source material.

3.1.15 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.

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

3.1.17 uncertainty: The estimated bounds of the deviation from the conventionally true value, generally expressed as a percent of the mean, ordinarily taken as the square root of the sum of the square of two components: 1) Random errors that are evaluated by statistical means; and 2) systematic errors that are evaluated by other means.

3.2 Abbreviations and Acronyms

AAI	Additional Acceptable Identification
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
CBP	Customs and Border Protection
CONEX	Container Express
cps	Counts per second
CWMD	Countering Weapons of Mass Destruction
DHS	Department of Homeland Security
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
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
LLNL	Lawrence Livermore National Laboratory
NII	Non-intrusive inspection
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
ppt	Parts per trillion
RI	Required isotopes
RIID	Radioisotope Identification Devices
RR	Required Radionuclide
SNM	Special Nuclear Material
SNL	Sandia National Laboratories
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	Less than or equal to 75%
Atmospheric pressure	70 kPa 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) at distance of closest approach
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	Natural conditions without the presence of man-made emitters

4.2 Uncertainties and Units

4.2.1 Uncertainties

Unless otherwise specified, the total combined uncertainty for any measurable quantity (e.g., radiation field), shall be documented and should not exceed 10% with an uncertainty coverage factor, k, of 1 (i.e., 1-sigma). This does not apply to background radiation measurements as such low uncertainty might not be possible to achieve. The uncertainty of the measured background shall be recorded.

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 (symbol: keV), 1 keV = 1.602×10^{-16} J, and mega-electron-volt (symbol: MeV), 1 MeV = 1.602×10^{-13} J.
- Exposure: Roentgen (symbol: R), 1 R = 2.58×10^{-4} Coulomb per kilogram (symbol: C/kg).
- Exposure rate: Roentgen per hour (symbol: R/h), 1 R/h = 2.58×10^{-4} C/kg/h.

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

The hand-held RIIDs 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 as they are covered sufficiently by the ANSI N42.34 standard [1].

These RIIDs typically acquire a gamma-ray spectrum and identify the radionuclide through comparison with an internal radionuclide library. RIIDs 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 RIIDs shall be capable of transmitting data to an accessible external location. The sent data shall comply with the ANSI N42.42 format and should validate against the N42 schema [4].

5.2 Instrument Usage

RIIDs are used in different operational scenarios. These scenarios are commonly described based on the type of item that is being screened as:

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

The items and vehicles being screened can be assumed to be stopped.

All RIIDs, independent of operational scenario where they are used, shall meet the requirements of this standard.

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 Configurations

The RIID shall, as a minimum, have the following two functional configurations:

Detection: displays a measurement of the radiation field 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 over an alarm threshold level. The alarm threshold and alarm on/off function shall be user settable. This configuration may provide dynamic radionuclide identification (e.g., radionuclides are identified by the RIID when sources are moving towards it).

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

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

5.4 Testing Parameters Requirements

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

Detection mode: measurement speed shall be 0.5 m/s (lower than average human walking speed as users will walk slower during a source search situation) at a distance of closest approach of 1 m. A detection is defined as an alarm. Alarm thresholds should be set based on ANSI N42.34 [1] to meet the false alarm rate requirements. The alarm threshold shall be set by the manufacturer.

Identification mode: the measurement time for the static identification mode shall be 60 seconds.

All RIIDs shall meet the minimum set of performance requirements per Section 6.

5.5 Source-to-Detector Distance during Measurements

For dynamic measurements used to test the detection mode, the requirements are based on the sources (listed in 5.8) being at a distance of closest approach of 1 m from the reference point of the RIID moving at a speed of 0.5 m/s. If the distance of closest approach, d (expressed in m), is adjusted (i.e., testing distance other than 1 m) to obtain the required radiation field strength, then the passage speed, v (expressed in m/s), shall be adjusted as follows:

$$v = v_0 \times d/d_0,$$

where $v_0 = 0.5 \text{ m/s}$ and $d_0 = 1$ m (with a tolerance of ±10%).

The maximum source to detector distance should not exceed 3 m from the center point of the source to the reference point of the RIID.

5.6 Scoring and Measurement Requirements

5.6.1 Test Replication

All tests shall be replicated 20 times.

5.6.2 Compliance with the Requirement

For each test and for each source, a RIID complies with a requirement if no more than 1 failure is observed in 20 trials (corresponds to a probability of approximately p = 0.79 with a 95% confidence level, or a probability p = 0.88 with an 80% confidence level, using the Agresti and Coull method).

5.6.3 Test Scoring

Tests for radionuclide identification of target sources shall be scored using Table 8 in Appendix A.

The appropriate RIID response depends on the type of target source measured. The response is correct when the RIID identifies the radionuclides present in the target source. The reporting of additional and background radionuclides is sometimes allowed. Appendix A details the CWMD scoring criteria as it applies to this standard.

5.6.4 Test Scoring: Exception for High Masking Ratio Test Cases

An exception is allowed for masking ratios involving masking ratios of 5:1 or greater. If the RIID is unable to identify the presence of highly enriched uranium (HEU) or weapons grade plutonium (WGPu) at the fluence rates for the masking sources defined in Table 5, Table 6, and Table 7 due to excessive count rates (at the energy region of interest for HEU and WGPu), then the RIID shall provide a message indicating that it cannot perform an identification. Possible displayed messages may include: degraded SNM performance, changes in minimum detectable activity (MDA) for the energy region of interest, high count rates in the region of interest, and detection of HEU and/or WGPu compromised.

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

5.7 Test Reporting

All identification results and alarms displayed by the RIID shall be recorded by the tester.

All spectra acquired from a test shall be saved. The saved file(s) shall include the identification results, alarms, radionuclide category [2], and confidence indication displayed for that test.

5.7.1 High-Purity Germanium (HPGe) Detector

The testing laboratory shall be equipped with a calibrated HPGe detector (i.e., known efficiency as a function of photon energy for a given source geometry). This HPGe detector shall be used for:

1. Determining the fluence rates of the sources used during testing.
2. Measuring the fluence rates used to determine masking ratios and shielding thicknesses.
3. Measuring the background radiation spectrum at the test location.
4. Checking for gamma-ray emitting impurities that could be present in the sources to be used for the tests; the impurity measurements shall be used to update the list of Additional Acceptable Identifications (AAI) [of radionuclides] in Table 9 of Appendix A. Radionuclides that could potentially be identified based on peaks observed in the source spectra (e.g., peaks due to scattering caused by the source configuration) may be added to the list provided in Table 9.

The energy response of the HPGe detector shall be measured prior to performing the radiation background measurements (see reference [12]).

Sources used for calibration of HPGe detectors shall be traceable to NIST (or equivalent national metrology institute, see [8], [9]) and should cover an energy range no smaller than 60 keV to 2.6 MeV. The calibration should be performed as described in ANSI N42.14 [12]. Information about calculating fluence rate is provided in Appendix B.

5.7.2 Gamma-ray Detector

A calibrated pressurized ionization chamber or energy compensated Geiger-Muller (GM) detector shall be used to provide a measurement of the ambient exposure rate at the test area.

The ambient exposure rate at the test area shall be monitored throughout the duration of the test.

5.7.3 Neutron Background Radiation

Neutron emitting sources or radiation fields should not be present at the test area throughout the duration of the test.

5.8 Source Configuration Requirements

5.8.1 ^{241}Am Emissions in WGPu Sources

The amount of ^{241}Am present 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 are comparable when tests are performed using different WGPu sources at different test locations.

To provide comparable test results, the emission rate (i.e., net peak area divided by the HPGe full-energy peak efficiency, see Appendix B) of the 60 keV line from ^{241}Am shall be no more than 10 times greater than that of the emission rate of the 375 keV line for ^{239}Pu (e.g., if the emission rate for the 375 keV line for ^{239}Pu is 100 s^{-1} then the emission rate for the 60 keV line for ^{241}Am shall not exceed 1000 s^{-1}). Copper listed in the American Society for Testing and Materials (ASTM) B152 with more than 99.9% Cu content should be used as the shielding material to reduce these low-energy emissions [14].

NOTE – Other materials such as cadmium or tin may be used to shield the source.

5.8.2 Shielded Industrial Sources

Shielded industrial sources used in this standard are in part based on International Atomic Energy Agency (IAEA) Categories 2 and 3 [14, 15]. These sources are typically encountered while shielded for transport and are normally shipped as White I or Yellow II packages [13]. The source configurations used for testing allows the tester to select from a range of source activities and shielding materials for large activity sources as if shipped as a Yellow II Type A package (see Table 2).

The fluence rate used for testing the RIID is determined outside the source shielding by summing the emission from all the measured source gamma-rays lines with energies greater than 40 keV (e.g., 662 keV line for ^{137}Cs, 1173 keV and 1332 keV lines in ^{60}Co).

Table 2. Shielded Industrial Sources

Radionuclide	Fluence Rate at Testing Point (photons/s/cm^2) §
^{60}Co	200 ± 20%
^{137}Cs	320 ± 20%

§ Uncertainties have a coverage factor, k, of 1 (1-sigma).

The fluence rates listed in Table 2 correspond to an exposure rate of approximately 0.45 mR/h at a distance of 1 m (or 5 mR/h at 30 cm) from the surface of the package, that is within the Department of Transportation (DOT) Yellow II packages (that allows for a maximum exposure rate of 1 mR/h at distance of 1 m).

For the dynamic tests, the sources are expected to produce the fluence rate listed in Table 2 at the reference point of the RIID when the sources are placed at a source-to-detector distance of 1 m and moving at a speed of 0.5 m/s. If the source-to-detector distance is not equal to 1 m then the testing speed shall to be scaled according to Section 5.5.

5.8.3 Bare and Shielded Sources

The HEU, WGPu, DU, and ^{237}Np sources used for the bare and shielded test cases shall conform to those listed in Table 3 and Table 4.

The fluence rates in Table 3 are based on using the 186 keV gamma-ray line for HEU, the 375 keV gamma-ray line for WGPu, and the 1001 keV gamma-ray line for DU. See Appendix B. Sources may be unshielded or shielded with steel or high-density polyethylene (HDPE). For the shielded test cases, the thickness of the shielding is such that the source emissions for the specified gamma-ray lines are reduced by 50%. For the shielded sources, the fluence rate is determined outside the shielding material. The sources shall be fully surrounded by the shielding material.

For each source configuration listed in Table 3 and Table 4, take a spectrum using a characterized HPGe detector and determine the fluence rate at the point where the reference point of the RIID will be located during the measurements, see Appendix B.3.

For the dynamic tests, the sources are expected to produce the fluence rates listed in Table 3 and Table 4 at the reference point of the RIID when the sources are placed at a source-to-detector distance of 1 m (for a source or detector moving at a speed of 0.5 m/s). If the source-to-detector distance is not equal to 1 m then the testing speed shall to be scaled according to Section 5.5.

Table 3. DU, HEU, and WGPu Shielded and Bare Source Configurations

Source	Shielding Material	Fluence Rate at Testing Point (photons/s/cm^2) *	Calculated shielding thickness (cm) †	Recommended shielding thickness based on commercially available materials (cm)
HEU	None	1.6 ± 20%	NA	NA
HEU	Steel	1.6 ± 20%	0.53	0.48
HEU	HDPE	1.6 ± 20%	5.37	4.71
WGPu	None	3.8 ± 20%	NA	NA
WGPu	Steel	3.8 ± 20%	0.94	0.95
WGPu	HDPE	3.8 ± 20%	6.86	6.99
DU	None	3.9 ± 20%	NA	NA
DU	Steel	3.9 ± 20%	1.47	1.27
DU	HDPE	3.9 ± 20%	11.13	11.11

* Uncertainties have a coverage factor, k, of1 (1-sigma).

† The shielding thickness has an uncertainty of ±10% (k=1).

The test cases using ^{237}Np are based on a bare source with no additional shielding or masking. The fluence rate is based on using the 143 keV gamma-ray line for ^{237}Np when the source is placed at a source-to-detector distance of 1 m.

Table 4. ^{237}Np Test Case

Source*	Fluence Rate at Testing Point (photons/s/cm^2)†	Distance (m)
^{237}Np	0.077 ± 20%	1

* Note: This source can also be acquired from commercial source manufacturers.

† This corresponds to a source mass of 90 mg or activity of 2.34 MBq with a 0.25 mm wall thickness stainless steel encapsulation. Uncertainties have a coverage factor, k, of 1.

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 0.2% ^{235}U.
- WGPu shall have no more than 6.5% ^{240}Pu and no less than 93% ^{239}Pu.

5.8.4 Masking Using Medical Sources

Testing per Section 6 shall be conducted using the source configurations described in Table 5. Measurements of the fluence rate for the target and masking sources shall be performed at the same distance as they are going to be located during the test. During testing the masking material shall be located near the target source (sources are co-located, distance between sources should not exceed 30 cm), 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, 375 keV for WGPu, 141 keV for ^{99m}Tc, 185 keV for ^{67}Ga, and 364 keV for ^{131}I. The fluence rate of the medical sources needs to be determined for the sources placed inside the polymethyl methacrylate (PMMA) shielding described in the next paragraph. To determine the fluence rate for each source, and subsequently determine masking ratios, place the target source in front of a characterized HPGe detector, at the distance at which the HPGe detector was characterized (correct for any differences in source encapsulation). Take a spectrum of the target source, obtain the net photo-peak area for the corresponding gamma-ray line, and determine the fluence rate using equation B.3.7. Place the medical source at the same location in front of the HPGe detector, take a spectrum using the same live time, obtain the net photo-peak area for the corresponding gamma-ray line, and determine the fluence rate using equation B.3.7. Use these measured values to determine the different masking ratios and the source locations relative to the RIID for each test. 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 5.

Medical sources used in this standard shall be surrounded by 7.5 cm of 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 [5].

Table 5. Masking with Medical Sources

Target Source Material	Fluence Rate of Target Source at Testing Point (photons/s/cm^2)*	Masking Source	Masking Ratios (Medical:Source)
HEU	1.6 ± 20%	^{99m}Tc	1:1, 5:1
HEU	1.6 ± 20%	^{67}Ga	1:1, 5:1
HEU	1.6 ± 20%	^{131}I	1:1, 5:1
WGPu	3.8 ± 20%	^{99m}Tc	1:1, 5:1
WGPu	3.8 ± 20%	^{67}Ga	1:1, 5:1
WGPu	3.8 ± 20%	^{131}I	1:1, 5:1

* Uncertainties have a coverage factor, k, of 1.

5.8.5 Masking Using Industrial Sources

Testing per Section 6 shall be conducted using the source configurations described in Table 6. The fluence rate for the target and masking sources shall be measured at the same distance as they are going to be located during the test.

During actual testing the masking material shall be located near the target source (sources are co-located, distance between sources should not exceed 30 cm) but neither source shall provide additional shielding of the other.

For masking test cases using bare industrial sources (i.e., unshielded industrial sources), the masking ratios are based on the fluence rate for the following gamma-ray lines: 662 keV for ^{137}Cs, 1332 keV for ^{60}Co, 186 keV for HEU, and 375 keV for WGPu. To determine the fluence rate for each source and masking ratios for each configuration, place the target source in front of a characterized HPGe detector, at the distance at which the HPGe detector was characterized (correct for any differences in source encapsulation). Take a spectrum of the target source, obtain the net photo-peak area for the corresponding gamma-ray line and determine the fluence rate using equation B.3.7. Place the industrial source at the same location in front of the HPGe detector, take a spectrum using the same live time, obtain the net photo-peak area for the corresponding gamma-ray line, and determine the fluence rate using equation B.3.7. Use these measured values to determine the different masking ratios and the source locations relative to the RIID for each test. Calculations of masking ratios should be based on background-subtracted spectra. Several sources (i.e., unshielded point sources) may be required to obtain the different masking ratios listed in Table 6. Testing is not carried out with the industrial sources listed in Table 2 due to the high radiation field produced by these sources. During testing the masking material shall be located near the target source (sources are co-located, distance between sources should not exceed 30 cm), neither source shall provide additional shielding of the other.

Table 6. Masking with Industrial Sources

Target Source Material	Fluence Rate of Target Source at Testing Point (photons/s/cm^2)*	Masking Source	Masking Ratios (Industrial:Source)
HEU	1.6 ± 20%	^{60}Co	1:1, 5:1
HEU	1.6 ± 20%	^{137}Cs	1:1, 5:1
WGPu	3.8 ± 20%	^{60}Co	1:1, 5:1

WGPu	3.8 ± 20%	^{137}Cs	1:1, 5:1

* Uncertainties have a coverage factor, k, of 1 (±1 sigma).

5.8.6 Masking Using Simulated NORM Sources

The simulation of bulk NORM sources shall be done by surrounding ^{226}Ra and ^{232}Th sealed sources with 10 cm of PMMA such that each source produces the same total fluence rate. See Appendix B. For this scenario the angle of incidence requirement listed in Table 1 does not apply (i.e., larger incidence angles may be used).

For the NORM source, the masking ratios shall be based on the sum of all the photo-peaks measured with a characterized HPGe detector in the NORM spectrum (including all photo-peaks from 40 keV to 2700 keV with emission probabilities that are 1% or larger) and the following gamma-ray lines for each target source: 186 keV line for HEU, the 375 keV line for WGPu, and the 1001 keV line for DU. Testing per Section 6 shall be conducted using the source configurations described in Table 7.

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.

To determine the appropriate fluence rate for masking ratios and the source locations relative to the RIID for each test, each target source should be measured by a characterized HPGe detector, at the distance at which the HPGe detector was characterized. Calculations of masking ratios shall be based on background-subtracted counts, not on measured gross counts.

The following steps should be followed to measure the NORM fluence:

1. Ensure that there are no sources in the vicinity; take a background spectrum at the measurement location.
2. Take a spectrum of the target source using the same live time as that of the background spectrum, obtain the net photo-peak area for the corresponding gamma-ray line, and determine the fluence rate using equation B.3.7.
3. Place the simulated NORM at the same location in front of the HPGe detector, take a spectrum using the same live time as the background spectrum, obtain the net photo-peak area for all the gamma-ray lines in the NORM spectrum and determine the fluence rate using equation B.3.7.
4. Subtract the background contribution (background net peak count rate) from each NORM peak (NORM net photo-peak area) and add the contribution from all the background subtracted NORM peaks to determine the fluence rate. Use this background-subtracted value to determine the different masking ratios listed in Table 7 and the source locations relative to the RIID for each test.

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 (sources are co-located, distance between sources should not exceed 30 cm), but neither source shall provide additional shielding of the other.

Table 7. Masking with NORM Sources

Target Source Material	Fluence Rate of Target Source at Testing Point (photons/s/cm^2)*	Masking Source†	Masking Ratios (NORM:Source)
HEU	1.6 ± 20%	Simulated NORM	1:1, 5:1
WGPu	3.8 ± 20%	Simulated NORM	1:1, 5:1
DU	3.9 ± 20%	Simulated NORM	1:1, 5:1

* Uncertainties have a coverage factor, k, of 1.

† The simulated NORM sources (^{226}Ra and ^{232}Th) were designed by NIST and are available for use. The ^{226}Ra and ^{232}Th are commercially available.

6 Radiological Tests

6.1 Single Radionuclide Detection and Identification—No Masking

6.1.1 Requirements

Detection mode: All RIIDs shall detect the bare and shielded target source test cases listed in Table 2, Table 3, and Table 4, based on the testing parameters in Section 5.4.

Identification mode: All RIIDs shall correctly identify the sources listed in Table 2, Table 3, and Table 4 using a measurement time of 60 s.

6.1.2 Test Method

Detection mode: For each test trial, one of the bare and shielded target source configurations in Table 2, Table 3, and Table 4 shall be moved past the RIID per the testing parameters in Section 5.4. The RIID performance complies with the TCS requirements if the RIID detects the radionuclides 19 of 20 times per Section 5.6. Ensure that the RIID background has been refreshed between trials per manufacturer's instructions during the measurements, if appropriate. There shall be a 10 s minimum delay between trials.

Identification mode: For each test trial, the RIID shall be exposed to one of the bare and shielded target source configurations in Table 2, Table 3, and Table 4 per the testing parameters in Section 5.4. The RIID performance complies with the TCS requirements if the RIID correctly identifies the radionuclide 19 of 20 trials for each source configuration, per Section 5.6. Ensure that the RIID background has been refreshed prior to placing the source in the test area per manufacturer's instructions, if appropriate.

6.2 Simultaneous Radionuclide Identification—Masking

6.2.1 Requirements

For the masking test cases listed in Table 5, Table 6, and Table 7, the results are going to be used only to assess the RIID performance; there is no pass/fail criteria for these sources.

6.2.2 Test Method

For each test trial, the RIID shall be exposed to one of the masked target source configurations in Table 5, Table 6, and Table 7 using a measurement time of 60 s. The RIID performance in 20 trials with each configuration will be recorded, data will be analyzed in accordance with Section 5.6 and Table 9. Ensure that the RIID background has been refreshed per manufacturer's instructions during the measurements, if appropriate.

6.3 Identifications Produced by Masking Radionuclides

6.3.1 Requirement

The RIID shall correctly identify the masking sources in Table 5 to Table 7 (i.e., simulated NORM (^{226}Ra and ^{232}Th), ^{60}Co, ^{137}Cs, ^{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. For this test, no target source is present.

6.3.2 Test Method

For this test, no target source is present. For each test trial, the RIID shall be exposed to one of the individual masking source configurations in Table 5, Table 6, and Table 7 in the tested configuration corresponding to a masking ratio of 5:1 using a measurement time of 60 s. The RIID performance complies with TCS requirements if the RIID correctly identifies the masking radionuclides 19 of 20 times per Section 5.6. Ensure that the RIID background has been refreshed per manufacturer's instructions during the measurements, if appropriate.

7 Documentation

7.1 Certificate

Documentation shall be provided as required in the ANSI N42.34 standard.

7.2 Operation and Maintenance Manual

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

Appendix A Scoring Definitions

For this standard, the alarm scoring logic listed in Table 8 shall be used.

Table 8. Detection Alarm Scoring Logic

Source	Detection System Alarm Response (Gamma Only)	Detection System Alarm Response (Neutron Only)	Detection System Alarm Response (Gamma & Neutron)	Detection System Alarm Response (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
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
WGPu + ^{60}Co	Correct	Correct	Correct	False Negative
WGPu + ^{137}Cs	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

Table 9 provides a summary of the Required Identifications (RIs) as well as Additional Acceptable Identifications (AAIs) for each test source. Table 9 shall be used for the radionuclide identification data analysis. Background radionuclides and radionuclides in the decay chain may be identified for all sources. A high resolution and high statistics spectrum should be acquired for all sources used for testing to determine potential impurities and radionuclide composition. The list of additional acceptable identifications (AAIs) listed in Table 9 should be updated based on the impurities and radionuclides measured in each source.

Table 9. Radionuclide Identification Reporting Used for Scoring

Source	Required Identification (at least one)	Additional Acceptable Identification
Simulated NORM	None	Thorium, Radium, ^{232}Th, ^{226}Ra, NORM
^{137}Cs	^{137}Cs	None
^{60}Co	^{60}Co	None
^{237}Np	^{237}Np	^{233}Pa
WGPu	^{239}Pu, Plutonium, Pu, WGPu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U
DU	^{238}U, Uranium, DU, U	^{235}U, ^{234m}Pa,
HEU	^{235}U, HEU, Uranium, U	^{238}U, ^{234m}Pa
^{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, HEU, Uranium, U	^{238}U, ^{234m}Pa, ^{60}Co
HEU + ^{137}Cs	^{235}U, HEU, Uranium, U	^{238}U, ^{234m}Pa, ^{137}Cs
HEU + ^{99m}Tc	^{235}U, HEU, Uranium, U	^{238}U, ^{234m}Pa, ^{99}Mo, ^{99m}Tc
HEU + ^{131}I	^{235}U, HEU, Uranium, U	^{238}U, ^{234m}Pa, ^{131}I
HEU + ^{67}Ga	^{235}U, HEU, Uranium, U	^{238}U, ^{234m}Pa, ^{67}Ga
HEU + Simulated NORM	^{235}U, HEU, Uranium, U	^{232}Th, ^{226}Ra, ^{238}U, ^{234m}Pa, Thorium, Radium, NORM
WGPu + ^{60}Co	^{239}Pu, Plutonium, Pu, WGPu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, ^{60}Co
WGPu + ^{137}Cs	^{239}Pu, Plutonium, Pu, WGPu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, ^{137}Cs
WGPu + ^{99m}Tc	^{239}Pu, Plutonium, Pu, WGPu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, ^{99}Mo, ^{99m}Tc
WGPu + ^{131}I	^{239}Pu, Plutonium, Pu, WGPu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, ^{131}I
WGPu + ^{67}Ga	^{239}Pu, Plutonium, Pu, WGPu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, ^{67}Ga
WGPu + Simulated NORM	^{239}Pu, Plutonium, Pu, WGPu	^{232}Th, ^{226}Ra, ^{238}U, ^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, Thorium, Radium, NORM
DU + Simulated NORM	^{238}U, Uranium, DU, U	^{235}U, ^{234m}Pa, ^{232}Th, ^{226}Ra, Thorium, Radium, NORM
No Source	None	None, NORM

For shielded sources that contain DU as part of the shielding, Table 10 provides an example of the

RIs as well as AAIs for test sources that could potentially be shielded with DU. The DU allows ^{235}U as a correct response because the 186 keV line is present in the DU spectrum. Similarly, the HEU allows ^{238}U as a correct response.

Table 10. Radionuclide Identification Reporting Used for Scoring for Sources Shielded with DU

Source	Required Identification	Additional Acceptable Identification
^{137}Cs	^{137}Cs	^{238}U, ^{235}U, ^{234m}Pa, Uranium, DU, U
^{60}Co	^{60}Co	^{238}U, ^{235}U, ^{234m}Pa, Uranium, DU, U

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. B2]:

$$\Gamma = 194.5\, h\nu\, (\mu_{ab}/\rho)_{\mathrm{air}} \qquad \text{(B.1.1)}$$

Where $h\nu$ is the energy of the photon emitted expressed in MeV and $(\mu_{ab}/\rho)_{air}$ is the mass 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:

$$\Gamma = 194.5 \sum_{i=1}^{n} N_i\, h\nu_i \left(\frac{\mu_{ab}^{i}}{\rho}\right)_{air} \qquad \text{(B.1.2)}$$

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

$$\dot{X} = \frac{\Gamma A}{d^2} \qquad \text{(B.1.3)}$$

Then the source activity can be estimated as:

$$A = \frac{\dot{X}\, d^2}{\Gamma} \qquad \text{(B.1.4)}$$

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:

$$\frac{I}{I_0} = \exp\left[-\left({}^{\mu}/_{\rho}\right) x\, \rho\right] \qquad \text{(B.1.5)}$$

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

Then for a shielded source or a source with an encapsulation or self-attenuation that can affect the source emission rate, the source activity can be approximated as:

$$A = \frac{\dot{X}\, d^2}{194.5 \sum_{i=1}^{n} N_i\, h\nu_i \left(\frac{\mu_{ab}^{i}}{\rho}\right)_{air} \exp\left[-\left({}^{\mu}/_{\rho}\right)_i x\, \rho\right]} \qquad \text{(B.1.6)}$$

B-2 Conversion Coefficients

Exposure rate can be converted to air-kerma rate by using the conversion equations for air listed in Table 11.

Table 11. Roentgen to Gray (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 (Gray, or Gy) to dose equivalent (Sievert, or 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 [7] and [10].

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 12.

Table 12. 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 x-rays)	1.73	1.65
^{137}Cs	1.20	1.06
^{60}Co	1.16	1.03

* ISO 4037:3

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.

$$\Phi = \frac{\mathrm{dN}}{\mathrm{da}} \qquad \text{(B.3.1)}$$

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

$$\dot{\phi} = \frac{d\Phi}{dt} = \frac{dN}{da\,dt} \qquad \text{(B.3.2)}$$

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:

$$\dot{\phi} = \frac{R}{4\pi r^2} \qquad \text{(B.3.3)}$$

where *R* is the number of photons per second emitted from the source. For a point source the number of photons per second emitted from the source is equal to the source activity times the emission probability of a gamma ray at energy *E*.

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

$$R = A * p(E) * \exp[-(\mu/\rho)\ x\ \rho] * B \qquad \text{(B.3.4)}$$

where *p(E)* is the emission probability of a gamma ray at energy *E*, and the source is encapsulated by layer of material with thickness, *x* (expressed in cm), densityρ (expressed in g/cm^3), *B* is the build-up factor, and μ/ρ is the mass attenuation coefficient of the material (expressed in units of cm^2/g). Then the fluence rate at a radius, *r*, from the source can be expressed as:

$$\dot{\phi} = \frac{A * p(E) * B * \exp[-(\mu/\rho)\ x\ \rho]}{4\pi r^2} \qquad \text{(B.3.5)}$$

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

$$\dot{\phi} = \frac{A}{4\pi r^2} \sum_i p(E_i)\, B_i \exp\left[-\left({}^{\mu}/_{\rho}\right)_i x\ \rho\right] \qquad \text{(B.3.6)}$$

Note that the fluence rate value obtained using equation (B.3.6) 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.

If the source is a point source of unknown activity (i.e., isotropic emission), 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:

$$\dot{\phi} = \frac{Area_{net}}{T_{live} * \epsilon(E) * 4\pi r^2} \qquad \text{(B.3.7)}$$

where $Area_{net}$ is the net photo-peak area of the gamma line of energy *E*, *ε(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]. This calculation assumes that the sources used for the detector efficiency calibration have the same encapsulation and they are measured in the same geometry and distance as the unknown sources. If this is not the case, the necessary corrections should be applied to the measurements.

Additional correction to the detector full-energy peak efficiency and/or net photo-peak area may be needed depending on the measurement conditions. These corrections may include the following: decay of the source during the measurement time, the source self-attenuation, attenuation and build-up factor through air from the source location to the detector location, attenuation through shielding material, build-up factor of shielding material, pile-up correction, coincidence summing correction and differences in source geometry (e.g., differences of HPGe calibration to measurement geometries).

Examples of fluence rate calculations for HEU and WGPu spherical sources are shown in the Table 13 and Table 14 below.

Table 13. 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 14. 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 Full-Energy-Peak Efficiency Calculations

The full-energy-peak efficiency is determined for a fixed source geometry (i.e., source-to-detector distance, source height, and source encapsulation) can be determined from gamma-ray lines in the gamma-ray spectrum by:

$$\epsilon(E) = \frac{Area_{net}}{A \times T_{live} \times P_{\gamma}} \qquad \text{(B.4.1)}$$

where the $Area_{net}$ is the net photo-peak area of the gamma-ray of energy E, A is the source activity at the time of the measurement, T_{live} is the measurement live time, and P_{γ} is the emission probability of the gamma-ray of energy E.

Correction coefficients to account for the source encapsulation and measurement distance shall be applied to the efficiency if the efficiency measurements and the source measurements are performed using different source geometries. Several corrections to the detector full-energy peak efficiency and/or net photopeak area may be needed depending on the measurement conditions. These corrections may include the decay of the source during the measurement time, the source self-attenuation, attenuation and build-up factor through air from the source location to the detector location, attenuation through shielding material, build-up factor of shielding material, pile-up correction, coincidence summing correction and differences in source geometry (e.g., differences of HPGe calibration to measurement geometries), see Ref. B3.

B-5 References

B1. 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. NIST IR 5632. J.H. Hubbell and S.M. Seltzer, May 2005. (http://www.nist.gov/pml/data/xraycoef/index.cfm)

B2. The Physics of Radiology, 4th Edition. Publisher Charles C. Thomas. Authors: Harold Elford Johns and John Robert Cunningham.

B3. Gamma- and X-ray Spectrometry with Semiconductor Detectors. K. Debertin and R.G. Helmer. Editor North-Holland. 1998 Edition.