Technical Capability Standard for Backpack Based Radiation Detection Systems

Domestic Nuclear Detection Office

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Homeland
Security

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Contents

Figures

Tables

Participants

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

Peter Chiaro, Chair

Leticia Pibida, Co-Chair

Organization	Representative
Customs and Border Protection	Warren Cluff
	John Donnachi
	John Hihn
	Michael Taylor
Domestic Nuclear Detection Office	John Blackadar
	Sandra Gogol
	Todd Pardue
	Don Potter
	Joseph Scallan
	Greg Slovik
	Jay Spingarn
	Robert Whitlock
	Brian Williams
Defense Threat Reduction Agency	Elizabeth Bartoz
DHS Science and Technology	Peter Shebell
Federal Bureau of Investigation	Bernard Bogdan
	John Kaysak
	Charles Pierce
	George Poillon
	Gabriel Sampoll-Ramirez
Federal Emergency Management Agency	William Billotte
Los Alamos National Laboratory	Mark Abhold

Lawrence Livermore National Laboratory	David Trombino
National Institute of Standards and Technology	Lisa Karam
	Michael Unterweger
National Nuclear Security Administration	Stephen Anderson
	Jason Crocker
	Gerald Garino
	Jason Semsprott
	Ed Roberts
Nuclear Regulatory Commission	Cynthia Jones
Oak Ridge National Laboratory	Chris Blessinger
Pacific Northwest National Laboratory	Thomas Deforest
	Michelle Johnson
	Daniel Stephens
Savannah River National Laboratory	Rudy Goetzman
	Al Goodwyn
United States Coast Guard	James Fisher
United States Navy	William Billotte

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 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.

It is anticipated that after a TCS is developed, the Domestic Nuclear Detection Office (DNDO) will work within the consensus standards arena to ensure that 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 are 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 America’s Security Affairs, Defense Threat Reduction Agency (DTRA), and several national laboratories (Los Alamos National Laboratory, Oak Ridge National Laboratory, Savannah River National Laboratory, and Pacific Northwest National Laboratory).

1.2 Scope

This TCS supplements ANSI/IEEE N42.53, “American National Standard Performance Criteria for Backpack-Based Radiation-Detection (BRD) Systems Used for Homeland Security.” The BRD TCS 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 backpack systems are covered by ANSI/IEEE N42.53 [1]. BRDs with a different form factor designed for similar applications should also meet the requirements stated in this TCS.

This technical capability standard addresses the mandate in the Security and Accountability For Every (SAFE) Port Act (H.R. 4954-16, Subtitle C – Port Operations, Section 121 (f) Standards) [2] 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 TCS is to supplement the radiological performance requirements established in ANSI N42.53. 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 N42.53 standard. This standard will be used by DNDO to test equipment performance, for example, through the Graduated Rad/Nuc Detector Evaluation and Reporting (GRaDER®) program [3].

2 Bibliography

The following documents are either used or referenced in the preparation of this TCS. If a reference doesn't have a date, then the most recent version applies.

[1] ANSI/IEEE N42.53 American National Standard Performance Criteria for Backpack Based Radiation Detection Systems Used for Homeland Security

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

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

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

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

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

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

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

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

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

[11] U.S. Department of Homeland Security, Domestic Nuclear Detection Office SECURITY CLASSIFICATION GUIDE, DHS SCG DNDO-001.1, December 2011.

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

[13] 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.

[14] 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.

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

[16] 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.

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.

Centerline: A real or imaginary line through the geometric center of the item, this line generally goes through the center of the length, width, or thickness of the item.

Center point: A real or imaginary point where the three mutually orthogonal lines that go through the center of the length, width and thickness of the item intersect.

Coverage factor: Numerical factor (k) used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty (ISO GUM: 1995).

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 of a radioactive source that is present or a radionuclide identification not reported by the instrument when a radioactive source is present.

False positive: An indication by the instrument that a radioactive source is present when the source is not present or a radionuclide identification reported by the instrument when the identified 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 [4])

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)

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

Reference point: Physical mark, or marks, used to position an instrument at a point where the conventionally true value of a quantity is to be measured. If the reference point of the BRD is not marked by the manufacturer, the horizontal and vertical center of the backpack shall be used as the reference point.

Special nuclear material (SNM): The term “special nuclear material” means plutonium, uranium enriched in the isotope 233 or in the isotope 235, but does not include uranium and thorium ores or any other material which is determined by the Nuclear Regulatory Commission (NRC) pursuant to the provisions of Section 61 to be source material. (Atomic Energy Act of 1954, as amended)

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.

3.2 Abbreviations and Acronyms

AAR	Additional Acceptable Radionuclide
ANSI	American National Standards Institute
BRD	Backpack radiation detector
CBP	Customs and Border Protection

DHS	Department of Homeland Security
DNDO	Domestic Nuclear Detection Office
DOE	Department of Energy
DTRA	Defense Threat Reduction Agency
DU	Depleted Uranium
FBI	Federal Bureau of Investigation
FWHM	Full Width Half Maximum
GRaDER®	Graduated Rad/Nuc Detector Evaluation and Reporting
HDPE	High Density Polyethylene
HEU	Highly Enriched Uranium
HPGe	High Purity Germanium
HPS	Health Physics Society
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
RR	Required Radionuclide
SI	International System of Units
SNL	Sandia National Laboratory
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.

The temperature and humidity ranges stated in Table 1 can be extended based on the results of tests performed in accordance with ANSI N42.53.

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 kPa to 106.6 kPa (525 to 800 mm of mercury at 0 °C)
Magnetic induction of external origin	Less than twice the value of the induction due to earth's magnetic field
Gamma Background Radiation (ambient photon exposure rate)	≤ 20 μR/h
Neutron Background Radiation	≤ 600 n/s/m^2

4.2 Units and Uncertainties

4.2.1 Uncertainties

The total uncertainty for radiation field measurements shall be documented. Component uncertainties (e.g., exposure rate detector) should not exceed 10% 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 practical, according to the SI system.

This standard also uses the following non-SI units for:

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

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

5 General Characteristics

5.1 General

BRDs addressed by this standard are used for the detection of gamma radiation and neutrons. They typically detect gamma radiation while moving, and may have radionuclide identification, source localization and neutron detection capabilities.

BRDs shall be capable of downloading data to an external location and shall be equipped with an alarm. They should be capable of real time data transfer to an external location and may have the ability to map radiological conditions.

5.2 Operational test modes

BRDs shall be evaluated in these operational test modes:

Static Mode: operation while the BRD and radioactive source(s) are not moving.

Dynamic Mode: operation while either the BRD or the source(s) is moving.

The performance requirements and testing methods for each operational test mode are described in Section 5.3.

5.3 Testing parameter requirements

The testing parameters depend on the BRD’s operational mode. The following parameters shall be used, unless otherwise specified in a particular test:

Static Mode: collection time for these measurements shall be 60 seconds, or less if specified by the manufacturer.

Dynamic Mode: measurements will be performed with either the BRD or the source moving at 1.2 m/s when the source-to-detector distance is 2 m. For larger distances, d, and the speed, v, should be scaled as v (m/s) = d (m) × 1.2/2.

An alarm is considered a detection.

All parameters and settings must be the same during both false alarm and sensitivity tests.

5.4 Source-to-detector distance during measurements

The fluence rate for each test source is based on a source to detector distance of 2 m. Sources with different masses may be used to provide the required fluence rate. The minimum source to detector distance is 1 m from the reference point of the BRD. ^{237}Np testing is optional. If testing is performed using ^{237}Np, the source as defined in Table 5 shall be placed at a distance of 1.5 m.

5.5 Backpack radiation detector setup during measurements

If the reference point of the BRD is not marked by the manufacturer, the horizontal and vertical center of the backpack, on the centerline as shown in Figures 1 and 2, shall be used as the reference point. The height of the center point of the source shall be the same as the center point of the BRD, 1.5 m from the floor or ground surface.

The BRD shall be configured as it would be used and mounted on a Polymethyl Methacrylate (PMMA) phantom similar to the one specified in ANSI N42.53. The minimum phantom dimensions shall be 40 cm wide, 60 cm high and 15 cm thick. The thickness of this phantom is based on the requirement for testing of personnel dosimeters from ANSI/HPS N13.11 [5]. The width and length suggested for this phantom ensures that the entire BRD is covered by the PMMA as required for dosimeters in the ANSI/HPS N13.11 standard.

5.6 Scoring and measurement requirements

5.6.1 Test replication

All tests shall consist of 10 trials unless otherwise specified in a specific test method.

5.6.2 Compliance with the requirement

For detection, a BRD complies with a requirement when a detection occurs in 10 out of 10 trials unless otherwise specified in a particular test.

For identification, a BRD complies with a requirement when the identification results are acceptable in 8 out of 10 trials.

5.6.3 Test scoring

The appropriate instrument response depends on the type of target source measured. The response is correct when the instrument identifies the target source. The reporting of additional radionuclides and background radionuclides is sometimes allowed. Appendix A provides details on the DNDO scoring criteria [10] as it applies to this TCS.

Radionuclide identification tests shall be scored using Categories C3 and C4 from the DNDO technical scoring criteria and Table 10 in Appendix A. For tests involving masking ratios of 10:1 or smaller, the BRD response shall be considered incorrect if the masking radionuclide is identified without the identification of the target radionuclide of interest.

Tests for radionuclide identification of masking sources with no target sources present (Section 6.3) shall be scored using Table 10 in Appendix A.

5.6.3.1 Test scoring – exception for high masking ratio test cases

For masking ratios greater than 10:1 if the BRD is unable to identify the presence of Highly Enriched Uranium (HEU) or Weapons Grade Plutonium (WGPu) for the masking sources defined in Tables 6, 7 and 8 due to excessive count rates (at the energy region of interest for HEU and WGPu), then the BRD shall provide a message (e.g., “potential masking agent”, “not identified”) indicating that the capability to identify HEU, WGPu or both is reduced. Methods for defining the masking ratios are described in Sections 5.9.4, 5.9.5 and 5.9.6.

5.7 Test reporting

The test results, including displayed information, shall be recorded and saved in addition to any output document (e.g., spectrum, data file) provided by the BRD.

5.8 Test facility and equipment

5.8.1 Test facility

The test facility shall be environmentally controlled in order to maintain standard test conditions as stated in Table 1. Radiation sources that are not part of a test shall be shielded and verified to not affect the radiation background during testing.

Instrumentation shall be available to monitor the environmental conditions as well as the ambient gamma and neutron background levels. For gamma, a calibrated High Purity Germanium (HPGe) detector shall be available for spectral measurements and a gamma detector for determination of the ambient background exposure rate. For neutron, a calibrated integrating neutron detector shall be available for neutron measurement.

The calibration of all monitoring instrumentation, including those devices used to monitor meteorological conditions, shall be traceable to NIST or another recognized organization.

5.8.2 Test equipment - HPGe

The HPGe detector shall be used for:

1. Obtaining the ground truth spectrum for each test source. The presence of gamma-ray emitting impurities can be determined by analyzing each spectrum using for example, GADRAS or PeakEasy. The impurity measurements will be used to update the list of Additional Acceptable Radionuclides (AARs) in Table 10 as needed.

2. Determining the emission rate for the shielded and masking ratio test cases, and to establish the required measurement distance and geometry.

3. Measuring and characterizing the radiation background at the test location.

The HPGe detector shall be calibrated according to ANSI/IEEE N42.14 [6]. Sources used to calibrate the HPGe detector shall be traceable to NIST or other recognized organization and cover an energy range of 60 keV to 2.6 MeV.

5.8.3 Test equipment – Gamma detector

An 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 and to monitor for changes in radiation level while tests are being performed. The energy response of the gamma detector from 60 keV to 1.33 MeV shall be known.

5.8.4 Test equipment – Neutron detector

The neutron detector shall be used to measure the neutron background at the test location. The neutron detector calibration shall be traceable to NIST and shall have the ability to integrate over a user selectable time interval. Integrated long counts are needed to obtain a more reasonable measurement of the neutron background fluence rate.

5.8.5 General test process

For each test, record the ambient meteorological conditions (temperature, relative humidity, and atmospheric pressure), background exposure rate (mean and standard deviation), gamma spectrum, integrated neutron counts, and neutron fluence rate at the test location.

A measurement shall be made using the HPGe detector and the neutron detector to verify test sources are not detected or identified by the BRD when the sources are placed away from the test area (i.e., at the end of the moving track for the dynamic measurements). These measurements shall be performed for 1 minute.

5.9 Source configuration requirements

5.9.1 ^{241}Am emissions from 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.

In order to provide comparable results, 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 the 414 keV line 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 listed in ASTM B152 with more than 99.9 % Cu content shall be used as the shielding material to reduce these low-energy emissions.

5.9.2 Shielded industrial sources

Industrial sources used by this TCS (Table 3) were selected based on International Atomic Energy Agency Safety Guide Categories 2 and 3 [8]. These sources are typically encountered while shielded for transport and depending on the radionuclide, activity, and package weight or size, are normally shipped as White I or Yellow II packages. The surface radiation limit and the limit at 1m are shown in Table 2.

Due to the possible differences in instrument response to high activity sources, testing using industrial sources will be used to characterize a BRD without a pass/fail criterion.

Testing shall be carried out using the sources listed in Table 3. Each source shall be placed inside its appropriate commercial shipping package or container. The dose rate produced by the source at 1 m from the surface of the shipping container shall be measured and recorded. The testing distances shall correspond to attenuations of 10 %, 30 %, 60 %, and 90 % of the main gamma-ray line net peak count rate listed in Table 3 relative to the measurements made at 1 m from the surface of the shipping container. The reference net peak count rate measurement is obtained at a distance of 1 m, the attenuation of the net peak count rate to 10 %, 30 %, 60 %, and 90 % shall be calculated using the $1/d^2$ law for the 1 m measurement. The HPGe detector shall be used to verify that the expected attenuation factors are obtained by measuring the gamma-ray line net peak count rate at the calculated distances.

NOTE – when using an HPGe detector to do these measurements, the dead time may be too large for the fields produced by these sources. In that case, the measurements used to determine the 10 %, 30 %, 60 %, and 90 % attenuation may be performed at a greater distance.

Record the measured and calculated exposure rate produced by the source at the centerline of the BRD as well as the distance from the source to the centerline of the BRD.

In addition, if the BRD has the ability to indicate when the radiation field is optimal for identification, that capability shall be used to establish the source distance. When using this capability record the measured and calculated exposure rate produced by the source at the centerline of the BRD as well as the distance.

Table 2: Shipping Labels for Radioactive Materials

Label	Surface Radiation level		Radiation level at 1 m
White I	< 0.5 mrem/h		Not applicable
Yellow II	< 50 mrem/h	AND	< 1 mrem/h
Yellow III	≥ 50 mrem/h	OR	≥ 1 mrem/h

Table 3: Industrial Sources

Radionuclide	Activity Range*	Main Gamma-ray Line
^{60}Co	0.8 – 8 Ci	1332 keV
^{137}Cs	3 – 30 Ci	662 keV
^{192}Ir	2 –20 Ci	317 keV
* These values were provided by the NRC		

5.9.3 Bare and shielded sources

The HEU and WGPu source emissions are based on a 1 kg and 400 g sphere respectively as defined in the TCS traceability memo [7]. The DU emission is based on a 2.5 kg plate with a surface area of approximately 400 cm^2 and a thickness of 0.3175 cm. For the BRD TCS it is required that these sources are detected at a distance of 2 m. The fluence rates for these sources are calculated based on these assumptions (see Appendix C, Section C2).

Sources with different masses, shapes, and forms may be used for testing. The HEU, WGPu, and DU sources used for the bare and shielded test cases shall conform to those listed in Table 4.

The fluence rates are based on 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 the shielded test case, the shielding material is added around each source without modifying the testing distance. The thickness of the shielding is such that the source emissions for the specific gamma-ray lines are reduced by 50 %. Calculated thicknesses of each shielding material are shown in Table 4. The recommended thicknesses shown in Table 4 represent commercially available materials that do not require machine tooling.

For each source configuration listed in Table 4, take a spectrum using the HPGe detector to determine the fluence rate where the reference point of the instrument will be located during testing (point of measurement), see Appendix C, Section C3. Sources shall be used bare, shielded with lead, steel, high density polyethylene (HDPE) and a combination of steel and HDPE.

Table 4: HEU, WGPu and DU Shielded and Unshielded Sources

Source	Shielding Material	Minimum Source Thickness (mm)*	Fluence Rate of the Source at the Reference Point (Photons/s/cm^2)**	Calculated Shielding Thickness (cm) †	Recommended Shielding Thickness Based on Commercial Availability (cm) ***
HEU	None	1	0.94 ± 10 %	NA	NA
HEU	Lead	1	0.94 ± 10 %	0.05	0.04
HEU	Steel	1	0.94 ± 10 %	0.53	0.48
HEU	HDPE	1	0.94 ± 10 %	5.37	4.71
HEU	Steel + HDPE	1	0.94 ± 10 %	0.26 Steel/2.68 HDPE	0.32/2.53
WGPu	None	5	2.30 ± 10 %	NA	NA
WGPu	Lead	5	2.30 ± 10 %	0.27	0.24
WGPu	Steel	5	2.30 ± 10 %	1.00	0.95
WGPu	HDPE	5	2.30 ± 10 %	7.18	7.98
WGPu	Steel + HDPE	5	2.30 ± 10 %	0.5 Steel/3.59 HDPE	0.48/3.78
DU	None	3	0.34 ± 10 %	NA	NA

Source thickness values are based on the 95% of infinite thickness emission rate.
**Uncertainties have a coverage factor, k, of 1.
† The shielding thickness has an uncertainty of ± 10 % (k=1).
***The DU thickness is based on commonly available standard reference materials.

The source configuration in Table 5 shall be used if performing the optional ^{237}Np tests. The ^{237}Np source is surrounded by 1cm of steel with no additional shielding or masking.

Table 5: Optional ^{237}Np Test Cases

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

5.9.4 Masking using medical sources

Testing per Section 6 shall be conducted using the source configurations described in Table 6. The target source and the masking source shall be placed at the same distance from the BRD when measuring the emission rate. During testing, the masking material shall be located near the target source but neither source shall shield the other. Several sources will be needed to perform all the masking tests. Additional shielding cannot be used to obtain the required masking ratios.

For masking test cases using medical sources, the masking ratios are based on the emission rates 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 (with the medical sources placed inside the PMMA). The gamma-ray emission rate is calculated using Equation (1).

$$-ray\ emission\ rate = \frac{Net\ peak\ area}{live\ time\ x\ full\ energy\ peak\ efficiency} \qquad (1)$$

To determine the emission rate for each source, and subsequently determine masking ratios, perform the following steps:

1. Ensure that there are no sources in the vicinity.
2. Take a 5 minute background spectrum at the measurement location. Verify that no sources are present in the background spectrum.
3. Place the HPGe detector at the target source test distance used for the bare measurements.
4. Take a spectrum of the target source until obtaining a minimum of 20,000 counts in the net peak area. Obtain the net peak area for the corresponding gamma-ray line and calculate the gamma-ray emission rate using Equation (1).
5. Remove the target source.
6. Place the medical source inside the PMMA at the same location as the target source (keeping the same source to detector distance) and repeat Step 4.
7. Use these measured values to determine the different masking ratios.

Masking ratios are determined using background subtracted spectra. Several sources of a given radionuclide may be required to obtain the different masking ratios listed in Table 6.

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.

Table 6: Masking With Medical Sources

Target Source Material	Fluence rate of target source at the reference point (photons/s/cm^2) *	Masking Source	Masking Ratios
HEU	0.94 ± 10 %	^{99m}Tc	40:1, 5:1
HEU	0.94 ± 10 %	^{67}Ga	40:1, 20:1, 10:1, 5:1
HEU	0.94 ± 10 %	^{131}I	40:1, 5:1
WGPu	2.30 ± 10 %	^{99m}Tc	40:1, 5:1
WGPu	2.30 ± 10 %	^{67}Ga	40:1, 5:1
WGPu	2.30 ± 10 %	^{131}I	40:1, 20:1, 10:1, 5:1
* Uncertainties have a coverage factor, k, of 1.			

5.9.5 Masking using industrial sources

Testing per Section 6 shall be conducted using the source configurations described in Table 7. The emission rate from 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 but neither source shall shield the other.

For masking test cases using industrial sources, the masking ratios are based on the emission rate for the following gamma-ray lines: 662 keV for ^{137}Cs, 317 keV for ^{192}Ir, 1332 keV for ^{60}Co, 186 keV for HEU, and 414 keV for WGPu.

To determine the emission rate for each source and masking ratios for each configuration perform the following steps:

1. Ensure that there are no sources in the vicinity.
2. Take a 5 minute background spectrum at the measurement location. Verify that no sources are present in the background spectrum.
3. Place the HPGe detector at the target source test distance used for the bare measurements.
4. Take a spectrum of the target source until obtaining a minimum of 20000 counts in the net peak area. Obtain the net peak area for the corresponding gamma-ray line and calculate the gamma-ray emission rate using Equation (1).
5. Remove the target source.
6. Place the industrial source at the same location as the target source (keeping the same source to detector distance) and repeat Step 4.
7. Use these measured gamma-ray emission rates to determine the different masking ratios.

Masking ratios are determined using background subtracted spectra. Several sources may be required to obtain the different masking ratios listed in Table 7.

Table 7: Masking With Industrial Sources

Target Source Material	Fluence rate of target source at the reference point (photons/s/cm^2)*	Masking Source	Masking Ratios
HEU	0.94 ± 10 %	^{60}Co	10:1, 5:1
HEU	0.94 ± 10 %	^{137}Cs	10:1, 5:1
HEU	0.94 ± 10 %	^{192}Ir	10:1, 5:1
WGPu	2.30 ± 10 %	^{60}Co	10:1, 5:1
WGPu	2.30 ± 10 %	^{137}Cs	10:1, 5:1
WGPu	2.30 ± 10 %	^{192}Ir	10:1, 5:1
* Uncertainties have a coverage factor, k, of 1.			

5.9.6 Masking using simulated NORM sources

For NORM masking test cases per Section 6, the masking ratio calculations shall be based on the count rate from 65 keV to 3 MeV corrected using the detector efficiency. The lower energy of 65 keV was selected 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 static mode and the relative intensity of the radioactive source emission measured by the detector would not vary for either a bulk or point source. In addition, the incident radiation 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 9 cm of PMMA. Each source should produce the same total radiation emission rate before surrounding them with PMMA. It is possible to use ^{232}U instead of ^{232}Th if the ^{232}U is at least 20 years old.

To determine the appropriate masking ratios perform the following steps:

1. Ensure that there are no sources in the vicinity.
2. Take a 5 minute background spectrum at the measurement location. Verify that no sources are present in the background spectrum.
3. Place the HPGe detector at the target source test distance used for the bare measurements.
4. Take a 5 min spectrum of the target source, subtract the background, divide the counts in every channel by the live time and the corresponding full-energy-peak efficiency and integrate the counts from 65 keV to 3 MeV.
5. Remove the target source.

6. Place the simulated NORM (i.e., masking source) at the same location as the target source, take a 5 min spectrum, subtract the background, divide the counts in every channel by the live time and the corresponding full-energy-peak efficiency and integrate the counts from 65 keV to 3 MeV.
7. Use these background subtracted gamma-ray emission rates to determine the different masking ratios listed in Table 8.

Masking ratios are determined using background subtracted counts. Several shielded ^{226}Ra and ^{232}Th sources may be required to obtain the different masking ratios.

For dynamic measurement, the target and the masking sources shall be collocated. For static measurements, it is allowed to have the masking sources in different locations relative to the target source in order to achieve the required masking ratio with a minimum number of sources.

Additional information for the simulated NORM and the masking ratio calculations can be found in Appendix B.

Table 8: Masking With NORM Sources

Target Source Material	Fluence Rate of Target Source ot The Reference Point (photons/s/cm^2) *	Masking Source	Masking Ratios
HEU	0.94 ± 10 %	Simulated NORM	30:1, 10:1
WGPu	2.30 ± 10 %	Simulated NORM	30:1, 10:1
DU	0.34 ± 10 %	Simulated NORM	30:1, 10:1
* Uncertainties have a coverage factor, k, of 1.			

5.9.7 Isotopic composition of sources

For this TCS, 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.

6 Radiological tests

6.1 False alarm test

This test is conducted to verify the operability at different test locations and confirm parameter settings. The ANSI N42.53 standard addresses false alarm tests for fixed and changing backgrounds

6.1.1 Requirements

When tested in an area with a stable background (only natural statistical fluctuations) at the levels stated in Table 1, the false alarm rate (for gammas, neutrons and radionuclide identification when applicable) shall be less than 1 alarm over a period of 1 h.

6.1.2 Test method

Observe the BRD over a period of 10 h in an area that has a controlled background (i.e., no additional radioactive sources present in the testing area during the duration of the test). Record the number of gamma, neutron (if neutron detection is available), and identification (if radionuclide identification capabilities are available) alarms observed over the 10 h test period. The results are acceptable if there are no more than 5 alarms or identifications over the test interval (based on 95% upper confidence bound for a Poisson distribution).

If the BRD does not meet this requirement, the operating parameter settings may be changed based on manufacturer provided information. The BRD shall be retested for false alarms. If acceptable, these new parameter settings shall be recorded and be kept fixed for the rest of the tests.

6.2 Single radionuclide detection and identification – No masking

6.2.1 Requirements

For the Static and Dynamic modes the instrument shall detect the single sources listed in Tables 3 and 4 using the measurement speeds listed in Section 5.3.

The BRD shall alarm no later than 2 seconds after the source passes through the distance of closest approach.

If the instrument has radionuclide identification capabilities, it shall correctly identify the sources listed in Tables 3 and 4 using the measurement time listed in Section 5.3 for the static mode.

The test shall be carried out with the BRD mounted on the phantom.

6.2.2 Test method

Static mode - This test is only performed if the BRD has radionuclide identification capabilities. The instrument performance is acceptable if the instrument can correctly identify the radionuclides 8 out of 10 trials.

For each trial the BRD shall be exposed to the bare and shielded source target quantities listed in Tables 3 and 4 per the testing parameters in Section 5.3. The test shall be carried out with the source placed at the calculated distance from the centerline of the BRD at the reference angle of 0° as described in Figure 2.

When testing with sources listed in Table 3, if the instrument provides a display that requires the user to move away from the source, follow the instrument prompts to determine the position of the measurement. Record the distance between the source and the centerline of the BRD at which the measurements were performed.

If the instrument requires periodic background updates, ensure that the instrument background has been refreshed per manufacturer's instructions between trials. Record the time needed to refresh the background.

Dynamic mode - The test is performed by linearly moving each source past the BRD at the speed listed in Section 5.3 parallel to the centerline of the BRD (see Figure 2). The test source shall start from a position where the BRD is not able to detect the source and then go past the BRD to a position where it is again not detected (i.e., instrument reading at background level). This can be achieved by distance or by the placement of shielding at end of travel. The BRD background shall not be refreshed between trials unless instructed by the manufacturer to do so.

There shall be 10 trials per source (5 trials in each direction of motion). The test shall be performed in two orthogonal planes as depicted in Figure 1 independently. For the vertical source plane, the backpack should be positioned parallel to the floor for testing. The test shall be performed by rotating the BRD (while mounted on the phantom) over the complete circle in 45º increments in the vertical and horizontal planes as shown in Figure 2 . Measure the time to alarm and the maximum number of counts (or count rate) for each trial. If the instrument has radionuclide identification capabilities, record the radionuclides identified in each trial.

The BRD shall alarm in 151 out of 160 total trials, when aggregating measurements for all angles shown in Figure 2 between 0º to 360º for each source, no later than 2 seconds after passing the point of closest approach between the BRD and the source. Calculate the intrinsic efficiency as a function of angle for each source.

Repeat the test without the phantom, as the BRD may be used as a standalone area radiation monitor.

In the vertical source plane as shown in Figure 1, the zero angle position is in the upward direction.

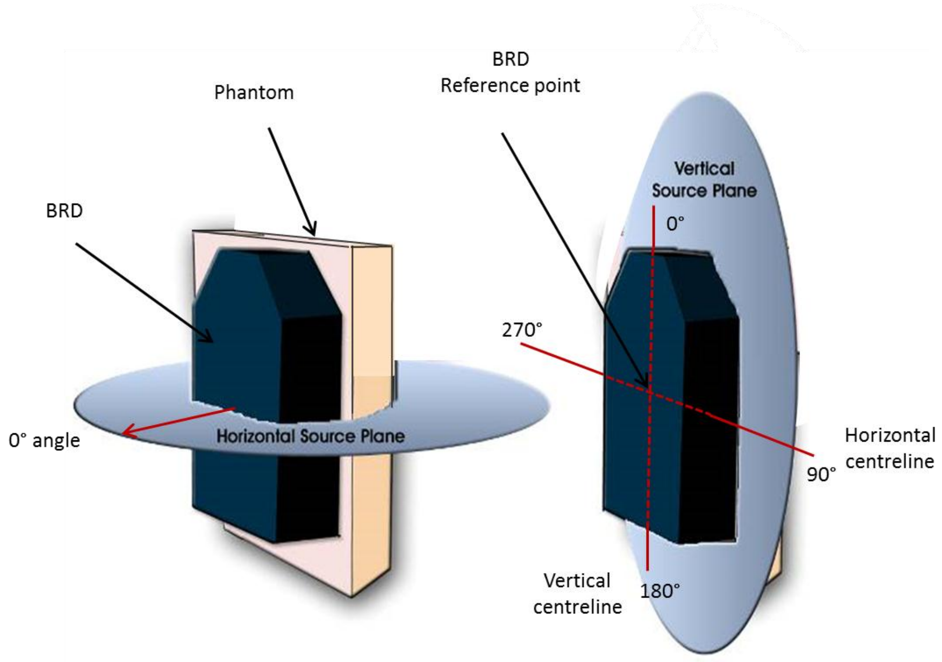

Figure 1: Diagram of Two Orthogonal Planes (Horizontal and Vertical Planes)

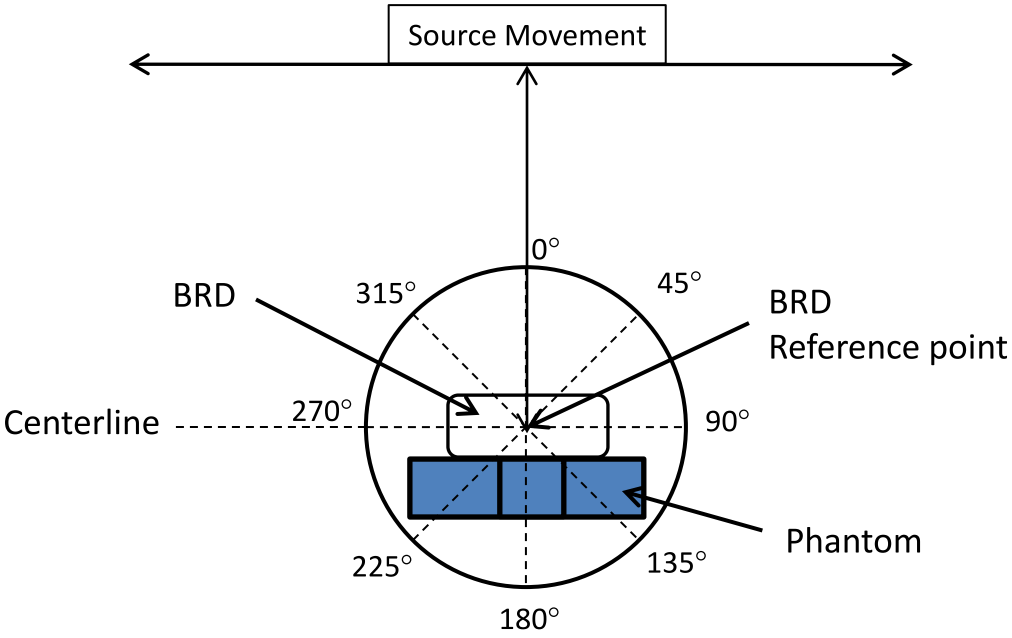

Figure 2 – Diagram of Testing Angles When Source Passes
at an Angle of 0°(top view)

6.3 Simultaneous radionuclide identification - masking

6.3.1 Requirement

The following test only applies to BRDs having radionuclide identification capability. The BRD shall identify the target sources in Tables 6, 7, and 8 for the masking test cases for static and dynamic modes at the measurement time listed in Section 5.3.

6.3.2 Test method

Static mode - For each test trial, the BRD shall be exposed to the masked sources in Tables 6, 7, and 8 using the measurement times listed in Section 5.3. The test shall be carried out with the source placed at a perpendicular distance from the centerline of the BRD at the reference angle of 0º in the horizontal source plane of the BRD where the required emission rate produced by the sources is limited by the test parameters listed in Section 5. The test shall be carried out with the BRD mounted on the phantom. The BRD background shall not be refreshed between trials unless instructed by the manufacturer to do so.

The instrument performance is acceptable if the instrument can correctly identify the radionuclides 8 out of 10 times within the measurement time listed in Section 5.3. Prior to the next trial, ensure that the instrument background has been refreshed per manufacturer's instructions, if appropriate.

For masking ratios greater than 10:1, the instrument shall be scored as described in Section 5.6.3.1.

Dynamic mode - The test is performed by linearly moving each source configuration (same configurations as used in the static mode) past the BRD at the speed listed in Section 5.3 parallel to the centerline of the BRD. The test shall be carried out with the BRD mounted on the phantom.

The test source shall start from a position where the BRD is not able to detect the source and then go past the BRD to a position where it is again not detected (i.e., instrument reading at background level). This can be achieved by distance or the placement of shielding at end of travel. Prior to the next trial, ensure that the instrument background has been refreshed per manufacturer's instructions.

The instrument performance is acceptable if the instrument correctly identifies the radionuclides 8 out of 10 times.

For masking ratios greater than 10:1, the instrument shall be scored as described in Section 5.6.3.1.

6.4 False positive identifications produced by masking radionuclides

6.4.1 Requirement

The following test only applies to BRDs having radionuclide identification capability. The BRD shall correctly identify the masking sources in Tables 6, 7 and 8 (simulated NORM, ^{60}Co, ^{137}Cs, ^{192}Ir, ^{67}Ga, ^{99m}Tc, and ^{131}I) in the tested configuration corresponding to masking ratios of 10:1 for the static and dynamic modes listed in Section 5.3, when no target source is present.

6.4.2 Test method

Static mode - For each test trial, the instrument shall be exposed to the masking sources in Tables 6, 7, and 8 in the test configuration corresponding to a masking ratio of 10:1 using the measurement times listed in Section 5.3. The test shall be carried out with the source placed at a perpendicular distance from the centerline of the BRD at the reference angle of 0º in the horizontal source plane of the BRD at the test parameters listed in Section 5. The test shall be carried out with the BRD mounted on the phantom.

The instrument performance is acceptable if the instrument correctly identifies the radionuclides 8 out of 10 times without producing any false positive responses. Prior to the next trial, ensure that the instrument background has been refreshed per manufacturer’s instructions, if appropriate.

Dynamic mode - The test is performed by linearly moving each source configuration (same configurations as used in the static mode) past the BRD at the speed listed in Section 5.3 parallel to the centerline of the BRD as shown in Figure 2. The test shall be carried out with the BRD mounted on the phantom. NOTE – testing may also be performed with the BRD plus the phantom moving past the static source configuration.

The test source shall start from a position where the BRD is not able to detect the source and then go past the BRD to a position where it is again not detected (i.e., instrument reading at background level). This can be achieved by distance or the placement of shielding at end of travel. Prior to the next trial, ensure that the instrument background has been refreshed per manufacturer’s instructions.

The instrument performance is acceptable if the instrument can correctly identify the radionuclides 8 out of 10 times without producing any false positive responses.

7 Documentation

7.1 Certificate

Documentation shall be provided as required in the ANSI N42.53 standard.

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 10. For this TCS, the alarm scoring logic listed in Table 9 shall be used.

Table 9: 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 by this TCS. Table 10 provides a summary of the required radionuclides (RRs) as well as the Additional Acceptable

Radionuclide (AARs) for each test source. In the DNDO technical scoring, NORM is not considered a source.

For the purposes of this TCS, 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 additional 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 Compromised, 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 detection system 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, a target source is present but 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 and 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 10 Radionuclide Identification Scoring Logic

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	^{239}Pu
^{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}T	^{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, ^{234m}Pa, 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

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Appendix B: **NORM information**

B1. Simulated NORM

Various types of sand that could be used for NORM masking were measured to determine isotopic content. The large variation in isotopic composition observed in the measured samples suggested the need to use a more reproducible NORM source to ensure that masking tests results are comparable when tests are performed at different laboratories. In order to develop the simulated NORM, several measurements were performed using ^{226}Ra and ^{232}Th point sources shielded by different materials in order to simulate a bulk spectrum and keep isotopic ratios similar to some of the measured sand samples. Measurements were performed using an HPGe detector.

Figure shows the energy spectra for different sand samples and for the point sources. The point sources used in these measurements are 20 µCi ^{232}U and 8 µCi ^{226}Ra shielded by 3.8 cm of PMMA. Spectra are normalized to the 2.6 MeV net peak areas. From Figure it can be observed that the contribution to the 185 keV gamma-ray line from the point source configuration is larger compared to that of the sand so additional shielding was added to reduce this contribution. The optimal PMMA thickness to match the 185 keV amount observed in the Australian Zircon sand was 9 cm. The ratios for different gamma-ray lines were calculated for different sands and different PMMA thicknesses for the ^{232}U and ^{226}Ra point sources (see Figure). These ratios were obtained using the net gamma-ray peak area measured using a calibrated HPGe (used the full-energy peak efficiency calibration measurements from 60 keV to 1.8 MeV of the HPGe detector).

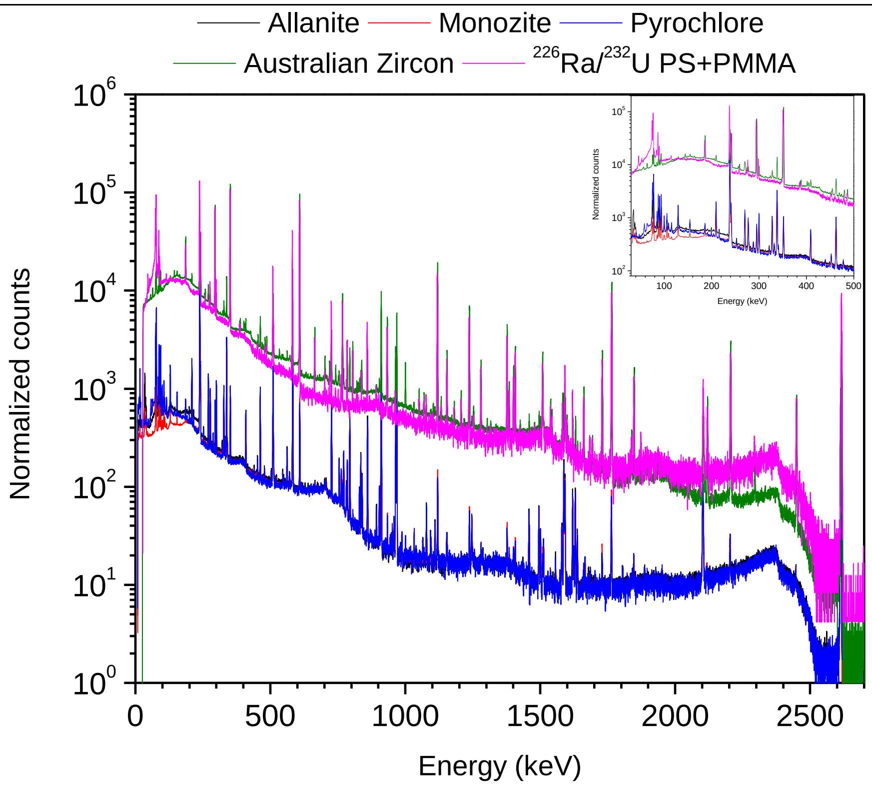

Figure 3: Spectra Of Different NORM Samples and Simulated NORM Using ^{226}Ra and ^{232}U Point Sources Surrounded By 3.8 cm of PMMA

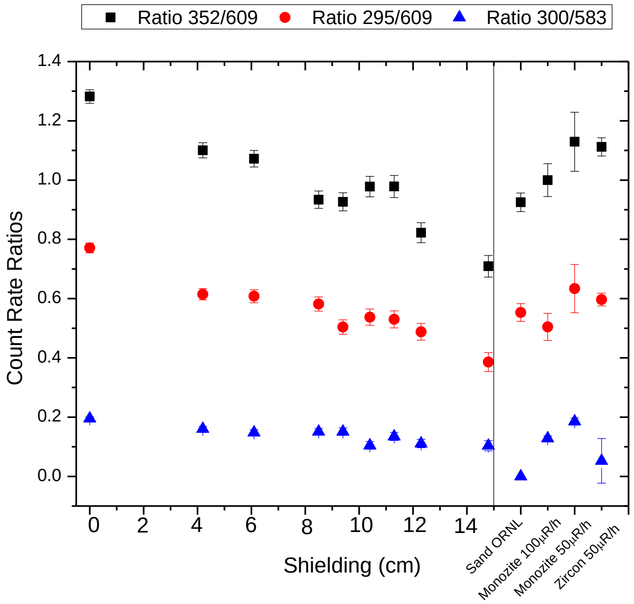

Figure 4: Ratios Of Main Gamma-Ray Lines for the NORM and Point Sources Spectra. The Point Sources Are Shielded With PMMA up to 15 cm Thick

B2. Masking ratios determination

During the development of the TCS for RIIDs, several measurements were performed at LANL to validate the standard requirements. These validation measurements included the determination of the NORM masking ratios based on the total flux (integration over the entire energy spectrum from 65 keV to 3 MeV) and on regions of interest around the main gamma-ray lines for HEU and WGPu produced by the NORM emission. For the regions of interest measurements, the following regions were used for the masking ratios calculations:

HEU: 160 keV – 200 keV

WGPu: 325 keV – 425 keV

An HPGe detector was used to acquire spectra for the HEU and WGPu sources when masked by the NORM source. The masking ratios were obtained using the total flux and the regions of interest. The differences in the energy spectra were very small (see Figure and Figure).

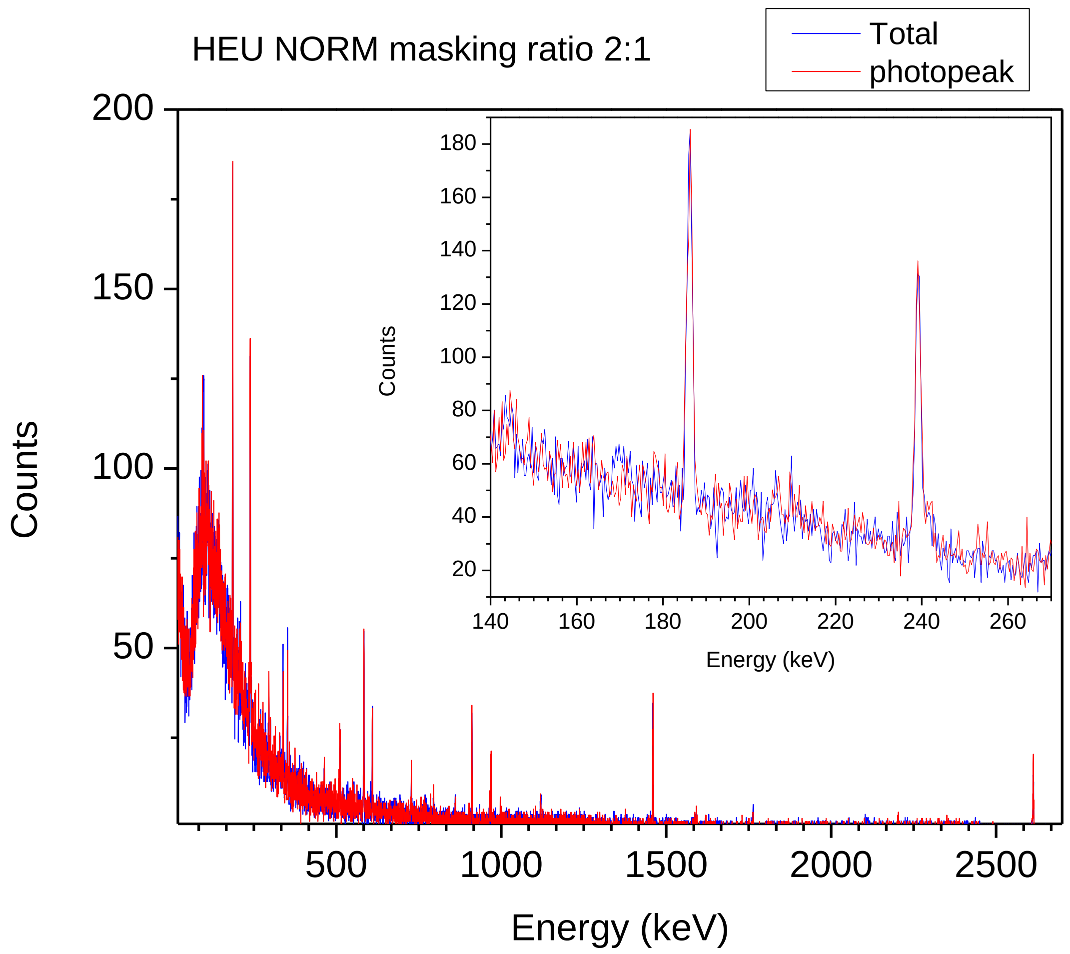

Figure 5: HPGE Spectra For HEU Source Masked With Sand, Masking Ratio Calculated Using Regions of Interest and Total Flux, Masking Ratio 2:1

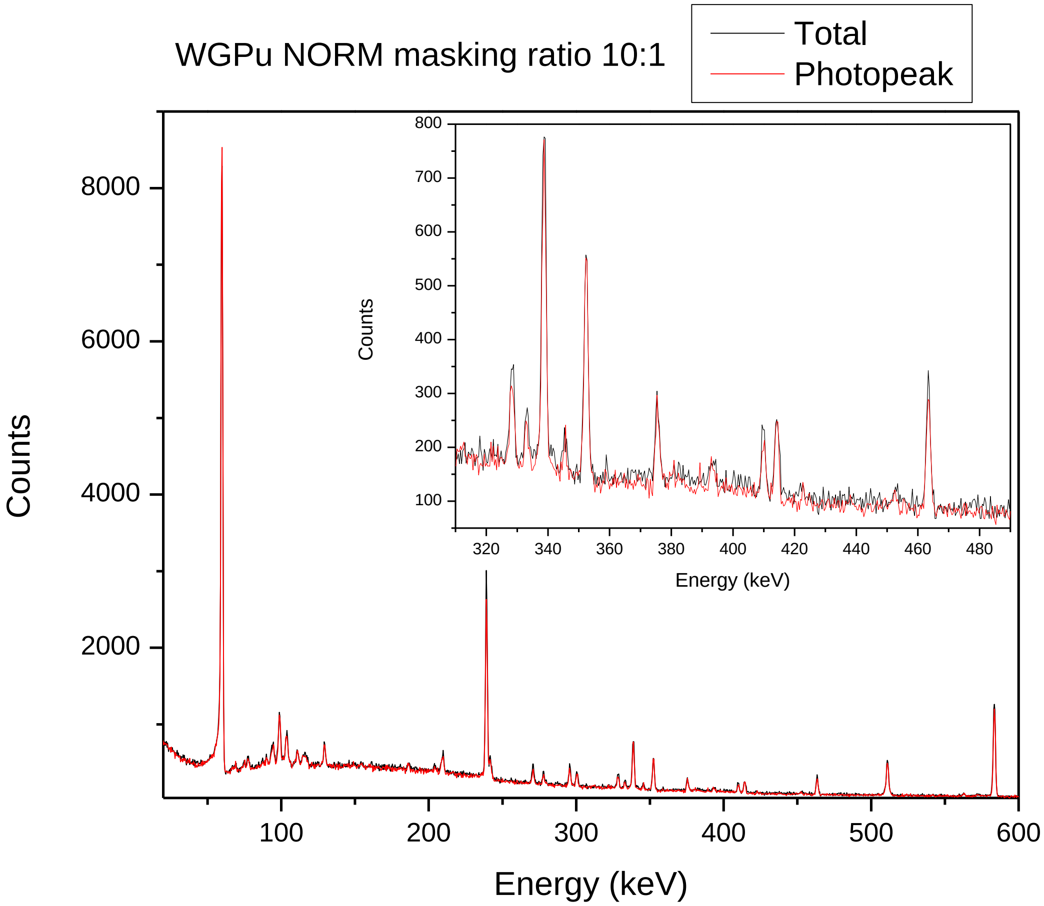

Figure 6: HPGe Spectra For WGPu Source Masked With Sand,
Masking Ratio Calculated Using Regions of Interest and Total Flux, Masking Ratio 10:1

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Appendix C: **Additional calculations**

The following provides a means to determine fluence rate at the test position or point of measurement.

C1. 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. Mono-energetic beams can be described by specifying the number of photons, dN that would cross an area, da, taken at right angles to the beam. The ratio of the number of photons that cross an area at right angles to the source is called the fluence or photon fluence by the International Commission of Radiological Units and Measurements (ICRU) and is represented by the Greek letter phi: ϕ.

$$\phi = \frac{dN}{da} \qquad \text{(C.1)}$$

The number of photons incident on a sphere of cross-sectional area da in the time interval dt is called the photon fluence rate or fluence rate and it is represented by $\dot{\phi}$, thus:

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

When the emission of the source is isotropic, the fluence rate at a radius, r, from the source can be expressed as:

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

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

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

$$R = A * p(E) \qquad \text{(C.4)}$$

where p(E) is the emission probability of a gamma ray at energy E.

The fluence rate can be then expressed as:

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

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

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

The emission probabilities listed in the Evaluated Nuclear Structure Data File (ENSDF) shall be used for the calculations using Equation (C.6). 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.

Note that the fluence rate value obtained using Equation (C.6) will depend on the cut-off energy used in the calculation. The lower energy value from the energy response range established by the applicable instrument standard shall be used when determining the fluence rate. Most gamma-ray detection instruments have difficulties detecting photons with energies lower than 30 keV.

C.2 Calculations of fluence rates for the SNM and DU sources

Calculations of fluence rates for the 1 kg HEU and 400 g WGPu spheres at 2 m were performed using Gamma Detector Response and Analysis Software (GADRAS). The calculations for the 2.5 kg DU plate were performed using a spectrum acquired by an HPGe detector.

In order to obtain the fluence rate values an HPGe detector was calibrated using NIST traceable point sources placed at distance of 1.5 m from the front face of the detector. The measured full-energy-peak efficiency is shown in Figure together with the associated 6th degree polynomial fit.

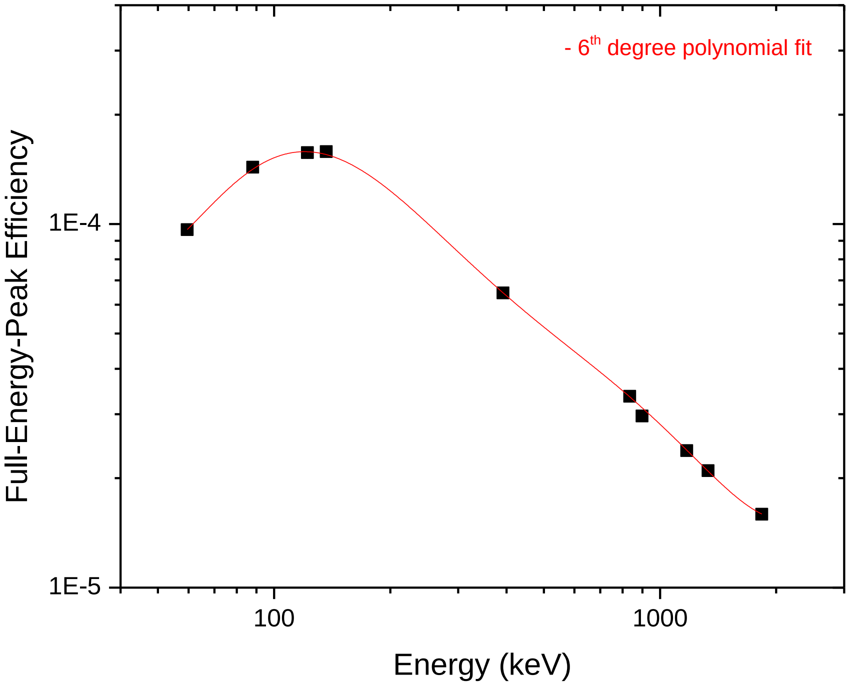

Figure 7: HPGe Detector Full-Energy-Peak Efficiency at 1.5 m

The acquired spectra for the point sources used for the HPGe detector calibration were used to obtain the detector response function in GADRAS. A spectrum of a (10 x 10 x 0.3175) cm DU plate was obtained using the same HPGe detector at source-to-detector distance of 1.5 m. The spectrum generated using a 1-D model with GADRAS was compared with the measured one (see Figure). The count rate provided by GADRAS for the 1001 keV gamma-ray line is 1.3 cps for the measured spectrum and 1.4 cps for the calculated one; this corresponds to a 7.7 % difference between the measured and calculated values.

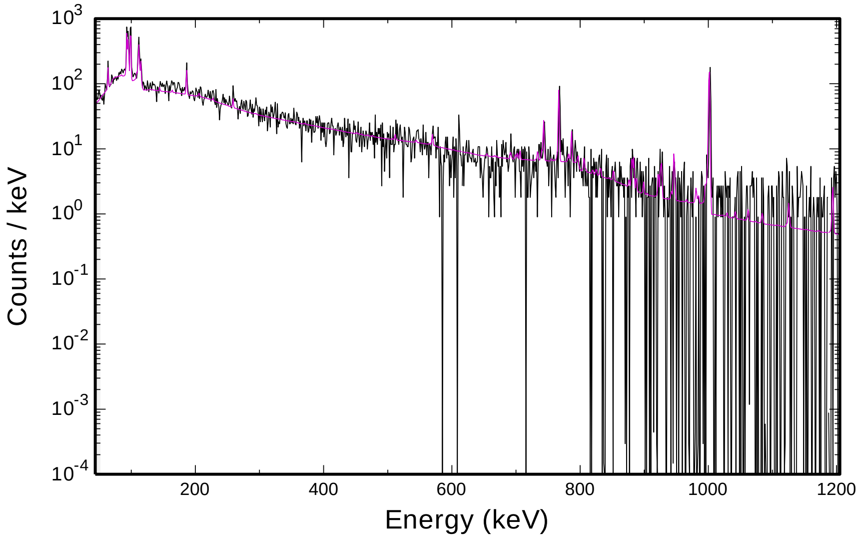

Figure 8: Measured and GADRAS Generated DU Plate Spectrum

The spectra for the 1 kg HEU and 400 g WGPu spheres were generated using the GADRAS 1-D model. The count rates of 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 at 1.5 m were obtained from GADRAS. The full-energy peak efficiency at 2 m was obtained from the 6th degree polynomial fit scaled by the square of the distance as shown in Equation (C.7). The fluence rate was calculated using Equation (C.8); where R_{net} is the net photo-peak area count rate (in counts per second) of the gamma line of energy E, ε(E) is the detector full-energy peak efficiency for the gamma-ray of energy, E, and d is the distance.

$$\epsilon(d = 2m) = \epsilon(d = 1.5m)\frac{(1.5m)^2}{(2m)^2} \qquad \text{(C.7)}$$

$$\dot{\phi} = \frac{R_{net}}{\epsilon(E)* \ 4\pi d^2} \qquad \text{(C.8)}$$

The results of the fluence rate calculations for HEU and WGPu spheres and DU plate are shown in Table 10.

Table 10: Summary Of Fluence Rate Calculations

Source	Mass (g)	Emission rate (Photon/s)	R_{net}[(1)] (cps)	$\epsilon(E)$[(1)]	Distance (cm)	Fluence rate (photons/s/cm^2)*
HEU	1000	4.70×10^5	16.5	$3.50\text{x}10^{-5}$	200	0.94
WGPu	400	1.15×10^6	17.9	$1.55\text{x}10^{-5}$	200	2.30
DU	2500	1.71×10^5	1.20	$6.99\text{x}10^{-6}$	200	0.34

(1) The HEU and WGPu emission rates were obtained using the GADRAS model for the specific HPGe detector. For the DU they were measured using the specific HPGe detector.
* The fluence rate estimated uncertainty is 9 % (1 standard deviation).

The differences in the photons per second determination for HEU and WGPu source at different distances using GADRAS is less than 4 %.

The densities and source enrichments used by the GADRAS 1-D model calculations are listed in Table 11.

Table 11: GADRAS Parameters

Source	Density (g/cm^3)	Enrichment
HEU	18.95	93.5 % ^{235}U, 5.3 % ^{238}U
WGPu	15.75	5.97 % ^{240}Pu, 93.06 % ^{239}Pu
DU	18.95	0.2 % ^{235}U, 99.8 % ^{238}U

C.3 Measurements

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

$$\dot{\phi} = \frac{Area_{net}}{T_{Live} * \epsilon(E) * 4\pi d^2} \qquad \text{(C.8)}$$

where $Area_{net}$ is the net photo-peak area (in counts) 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. B1.1].

References:

B1.1. Gamma- and X-ray Spectrometry with Semiconductor Detectors. K. Debertin and R.G. Helmer. Editor North-Holland. 1998 Edition.

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