Technical Capability Standard for Vehicle Mounted Mobile Systems

Domestic Nuclear Detection Office

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Homeland Security

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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), the Office of the Assistant Secretary of Defense for Homeland Defense and Americas' Security Affairs, Defense Threat Reduction Agency (DTRA), and several national laboratories (Los Alamos National Laboratory, Oak Ridge National Laboratory, Savannah River National Laboratory, Sandia National Laboratories, and Pacific Northwest National Laboratory).

1.2 Scope

This TCS supplements ANSI/IEEE N42.43, "American National Standard Performance Criteria for Mobile and Transportable Radiation Monitors Used for Homeland Security." The Mobile TCS establishes performance requirements for the detection and identification of special nuclear materials (SNM) and selected industrial radionuclides, both bare and shielded. This TCS 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 mobile systems are covered by ANSI/IEEE N42.43 [1].

Radiation detection systems addressed by this TCS are vehicle mounted and operate while the vehicle is in motion or static.

This TCS 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 N42.43. 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 N42.43 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

[1] ANSI/IEEE N42.43 American National Standard – American National Standard Performance Criteria for Mobile and Transportable Radiation Monitors 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 the 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] U.S. Department of Homeland Security, Domestic Nuclear Detection Office, Document Number 200-DNDO-107500v2.00, "DNDO Scoring Criteria".

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

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

[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.

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

Detection assembly: The component of the mobile radiation system that contains the detectors and associated electronic devices.

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)

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.

Mobile system: Detection system that is vehicle mounted and can operate while the vehicle is in motion or static.

Point of measurement: Location where the conventionally true value is known and where the reference point of the instrument is placed for testing.

Reference point: A real or imaginary point of intersection of three mutually orthogonal lines that pass through the center of the length, width and thickness of the detection assembly.

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
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 N42.43.

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

4.2.3 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

ANSI N42.43 establishes the general requirements for mobile systems, with gamma radiation detection and optional detection of neutrons and radionuclide identification. In this TCS, mobile systems are required to:

- detect gamma radiation,
- detect neutrons,
- perform radionuclide identification, and
- identify on which side a detected radiation source is located for multi-sided mobile systems.

Mobile systems may have mapping capabilities to provide the user with a map of radiation measurement results. Verification tests of the mapping capability are not addressed in this TCS.

5.2 Operational test modes

The mobile systems shall be evaluated in these operational test modes:

Static mode: operation while the system and radioactive source(s) are not moving.

Dynamic mode: operation while the system or source is moving in relation to each other (e.g., conducting commercial vehicle inspections, monitoring persons at a public event, conducting an area sweep). Testing while both are in motion is excluded. The relative direction of motion is depicted in Figure 1.

NOTE – Effects from changes in background while the system is in motion or being approached by a source are tested in ANSI N42.43 and are therefore not addressed in this TCS.

If the mobile system has multiple background update modes (e.g., fixed, sliding), tests should be performed for each mode, unless the manufacturer recommends the use of only one mode. Testing a mobile system to changing background levels is addressed in the ANSI N42.43 standard. Results from those tests should be reviewed prior to moving forward with the selection of background update mode and test process.

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

5.3 Testing parameter requirements

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

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

2. ***Dynamic mode:*** measurements will be performed with the radioactive source or mobile system moving at 3 speeds (v_0): 8 km/h (5 mph), 24 km/h (15 mph), and 48 km/h (30 mph).

The source-to-reference point distance is 3 m. For other distances, *d*, the speed, *v*, should be scaled as $v\ (km/h) = d\ (m) \times v_0/3$.

Testing shall be performed with the system mounted in a configuration as it would be used (e.g., inside a vehicle). The configuration shall be fully described in the test record.

All system parameters and settings must be the same during both false alarm and detection 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 3 m. Sources with different masses may be used to provide the required fluence rate. The minimum source to detector distance is 3 m from the reference point of the mobile system. ^{237}Np testing is optional. If testing is performed using ^{237}Np, the source as defined in this standard in Table 5 shall be placed at a distance of 3 m.

5.5 Detection zone and reference point

5.5.1 Detection zone

For testing purposes, the vertical length of the detection zone shall be 0.5 m to 2.5 m above the ground level (ANSI N42.43).

5.5.2 Reference point

Unless otherwise stated by the manufacturer, the reference point is the center point of the detector face or side of vehicle to which the detection assembly is mounted. The location of the detection assembly does not affect the height of the detection zone as defined in 5.5.1.

Figure 1 shows an overhead view of a two-sided system mounted to the bed of a pickup truck or utility trailer.

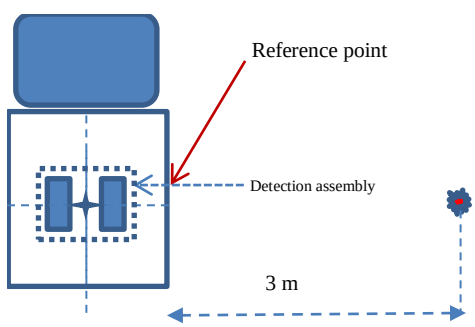

Figure 1: Reference Point Diagram for a Two-Sided Mobile System

5.6 Scoring and measurement requirements

5.6.1 Test replication

All tests shall consist of 20 trials, unless otherwise specified. Direction of travel, by either the source or the detection system, should be divided equally. For double-sided mobile systems, 10 trials shall be carried out on each side of the mobile system (i.e., for a total of 20 trials per source configuration).

5.6.2 Compliance with the requirement

Detection results are in compliance with a requirement when a detection occurs in each of the 20 trials, unless otherwise specified.

For identification, a mobile system is in compliance with a requirement when no more than 2 failures are observed in 20 trials.

5.6.3 Test scoring

The appropriate system 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 by the system is sometimes allowed. Radionuclide identification tests shall be scored using Categories C3 and C4 from the DNDO technical scoring criteria [5] and Table 11 in Appendix A as it applies to this TCS.

For tests involving masking ratios of 10:1 or smaller, the system response shall be considered incorrect if the masking radionuclide is identified without the identification of the target radionuclide of interest.

5.6.3.1 Identification test scoring – exception for high masking ratio test cases

For masking ratios greater than 10:1, if the system 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 system 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

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

5.8 Test facility and equipment

5.8.1 Test facility

The test location shall have instrumentation 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 radiation, an integrating neutron detector shall be used for neutron background measurement. Radiation sources that are not part of the tests defined by this TCS shall be shielded or moved and verified to not affect the radiation background during testing.

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 bare and in its test configuration. 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 11, 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 to determine if the background is contaminated by the presence of unexpected sources.
4. 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 measure the ambient exposure rate at the test area and to monitor for changes in radiation levels 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 for the measurement of the neutron background at the test location. The detector shall have the ability to integrate over an operator selectable time interval 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. Testing shall be performed in an area with known background.

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

NOTE - Testing with industrial sources is only used to characterize a mobile system response. Therefore, there are no pass/fail criteria for these tests.

Testing shall be carried out using the industrial sources listed in Table 3. They were selected based on International Atomic Energy Agency (IAEA) Safety Guide Categories 2 and 3 [8]. These sources are typically encountered while shielded for transport. Depending on the radionuclide, activity, and package weight and/or size, sources are normally shipped as White I or Yellow II packages. The surface radiation limit and the limit at 1 m are shown in Table 2.

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 as well as the source's activity.

For static measurements, mobile systems shall be characterized as to their response to the sources listed in Table 3 at distances corresponding to attenuations of 10 %, 30 %, 60 %, and 90 % of the main gamma-ray line. The attenuations shall be based on the gamma-ray line net peak count rate obtained relative to the 3 m test distance. The reference net peak count rate measurement is obtained at a distance of 3 m. The attenuation of the net peak count rate to 10 %, 30 %, 60 % and 90 % shall be calculated using the $1/d^2$ law from the 3 m measurement. An 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.

Record the measured and calculated exposure rate produced by the shielded source at each test distance (source to reference point).

For static identification measurements, if the system 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 test distance, as well as the measured and calculated exposure rate produced by the source at that distance (source to reference point).

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 SNM 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 rate is based on a 2.5 kg plate having a surface area of approximately 400 cm^2 and a thickness of 0.3175 cm. For the mobile system TCS, it is required that these sources are detected at a distance of 3 m from the reference point. The fluence rates for these sources are calculated based on these assumptions. See Appendix C for additional information regarding the determination of fluence rates used for testing.

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 the sources 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 will be located during testing (point of measurement), see Appendix C. 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 Bare Sources

Source	Shielding material	Minimum source thickness (mm)*	Fluence rate of the source at reference point (photons/s/cm^2)**	Calculated shielding thickness (cm) †	Recommended shielding thickness based on commercial availability (cm)***
HEU	None	1	0.42 ± 10 %	NA	NA
HEU	Lead	1	0.42 ± 10 %	0.05	0.04
HEU	Steel	1	0.42 ± 10 %	0.53	0.48
HEU	HDPE	1	0.42 ± 10 %	5.37	4.71
HEU	Steel + HDPE	1	0.42 ± 10 %	0.26 Steel/2.68 HDPE	0.32/2.53
WGPu	None	5	1.02 ± 10 %	NA	NA
WGPu	Lead	5	1.02 ± 10 %	0.27	0.24
WGPu	Steel	5	1.02 ± 10 %	1.00	0.95
WGPu	HDPE	5	1.02 ± 10 %	7.18	7.98
WGPu	Steel + HDPE	5	1.02 ± 10 %	0.5 Steel/3.59 HDPE	0.48/3.78
DU	None	3***	0.15 ± 10 %	NA	NA

*Source thickness values are based on the 95% of infinite thickness emission rate, see Reference 8.
**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. The ^{237}Np source is surrounded by 1 cm of steel with no additional shielding.

Table 5: Optional ^{237}Np Test Cases

Target Source	Quantity	Distance (m)	Shielding material	Shielding thickness	Masking source	Masking ratio
^{237}Np	90 mg	3	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 mobile system when measuring the emission rate. During actual testing, the masking source shall be located near the target source but neither source shall shield the other.

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 [10].

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).

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

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 an HPGe detector 3 m from the target source.
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), take a spectrum 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).
7. Use these measured gamma-ray emission rates 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.

Table 6: Masking with Medical Sources

Target Source Material	Fluence rate of target source at reference point (photons/s/cm^2)*	Masking Source	Masking Ratios
HEU	0.42 ± 10 %	^{99m}Tc	40:1, 5:1
HEU	0.42 ± 10 %	^{67}Ga	40:1, 20:1, 5:1
HEU	0.42 ± 10 %	^{131}I	40:1, 5:1
WGPu	1.02 ± 10 %	^{99m}Tc	40:1, 5:1
WGPu	1.02 ± 10 %	^{67}Ga	40:1, 5:1
WGPu	1.02 ± 10 %	^{131}I	40:1, 20:1, 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 source 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 an HPGe detector 3 m from the target source.
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 industrial source at the same location as the target source, take a spectrum 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).
7. Use these measured gamma-ray emission rates to determine the different masking ratios.

Masking ratios are determined using background subtracted spectra. Several sources or different distances (Section 5.9.2) may be required to obtain the different masking ratios listed in Table 7. The target sources shall be placed at the distance defined in Section 5.4. The masking source shall not shield the target source.

Table 7: Masking with Industrial Sources

Target Source Material	Fluence rate of target source at reference point (photons/s/cm^2)*	Masking Source	Masking Ratios
HEU	0.42 ± 10 %	^{60}Co	10:1, 5:1
HEU	0.42 ± 10 %	^{137}Cs	10:1, 5:1
HEU	0.42 ± 10 %	^{192}Ir	10:1, 5:1
WGPu	1.02 ± 10 %	^{60}Co	10:1, 5:1
WGPu	1.02 ± 10 %	^{137}Cs	10:1, 5:1
WGPu	1.02 ± 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 an HPGe detector 3 m from the target source.
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.

The target sources shall be placed at the distance defined in Section 5.4. The masking source shall not shield the target source.

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 at reference point (photons/s/cm^2) *	Masking Source	Masking Ratios
HEU	0.42 ± 10 %	Simulated NORM	30:1, 10:1
WGPu	1.02 ± 10 %	Simulated NORM	30:1, 10:1
DU	0.15 ± 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 parts per trillion (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 Static false alarm test

This test is conducted to verify operability at different test locations and confirm parameter settings. Detection tests shall be performed after this false alarm test using the same parameter settings. The ANSI N42.43 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 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 mobile system 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 test). Record the number of gamma alarms, neutron alarms, and identifications 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 mobile system does not meet this requirement, the parameter settings may be adjusted based on manufacturer-provided information and the mobile system shall be retested for false alarms. These settings shall be recorded, and kept fixed for the rest of the tests.

6.2 Single radionuclide detection and identification – no masking

6.2.1 Requirements

The system shall be tested as to its ability to detect and identify the sources listed in Tables 3 and 4 at the measurement speeds and time listed in Section 5.3.

6.2.2 Test method

Static mode for identification - For each test trial, the system shall be exposed to the bare and shielded sources listed in Tables 3 and 4 per the testing parameters in Section 5.3. The test shall be carried out with the source (or source configuration) placed at 0.5, 1.5, and 2.5 m from the floor or ground surface and at the source to detector distance based on the fluence rate requirement (see Section 5.4). Once the source is in position, the user shall initiate an identification per the manufacturer's specifications with the results recorded at the end of the measurement. Prior to each trial, ensure that the system background has been refreshed per manufacturer's instructions, if appropriate. The results from each series of tests for each configuration and test height are evaluated using Section 5.6.

Dynamic mode for detection - For each test trial, the bare and shielded sources listed in Tables 3 and 4 shall be moved past the system (or the system moved past the source) per the testing parameters in Section 5.3. The test shall be carried out with the source at 0.5, 1.5, and 2.5 m from the floor or ground surface and at the source to detector distance based on the fluence rate requirement (see Section 5.4). Prior to each trial, ensure that the system background has been refreshed per manufacturer's instructions, if appropriate. The results from each series of tests for each configuration and test height are evaluated using Section 5.6. If the system has automatic radionuclide identification capabilities, those results shall also be evaluated per Section 5.6.

6.3 Simultaneous radionuclide detection and identification – masking

6.3.1 Requirement

The system shall detect and identify the target sources listed in Tables 6, 7, and 8 when tested in the dynamic mode and static mode as defined in Section 5.3. The system shall specify on which side of the vehicle the source is detected if that capability is available.

6.3.2 Test method

Each source pair as listed in Table 9 at the source intensities listed in Tables 6, 7, and 8 will be configured as shown in Figure 2. Each target source shall be placed at the test distance used in Section 6.2. Each masking source shall be placed at the appropriate distance based on the masking ratio and fluence rate.

For the dynamic mode, the mobile system shall pass by source pair configurations 1 and 2 (or the sources shall pass by the mobile system) per the testing parameters in Section 5.3. Prior to each trial, ensure that the system background has been refreshed per manufacturer's instructions, if appropriate. The results from each series of tests for each configuration and test height shall be evaluated per Section 5.6. If the system has automatic radionuclide identification capabilities, those results shall also be evaluated per Section 5.6 as well.

For the static mode, the system shall be exposed to each configuration 1 source combination per the test parameters in Section 5.3 at the 1.5 m test height. Once the source combination is in position as shown in Figure 2, the user shall initiate an identification per the manufacturer's specifications with the results recorded at the end of the measurement. Prior to each trial, ensure that the system background has been refreshed per manufacturer's instructions, if appropriate. The results from each series of tests shall be evaluated per Section 5.6.

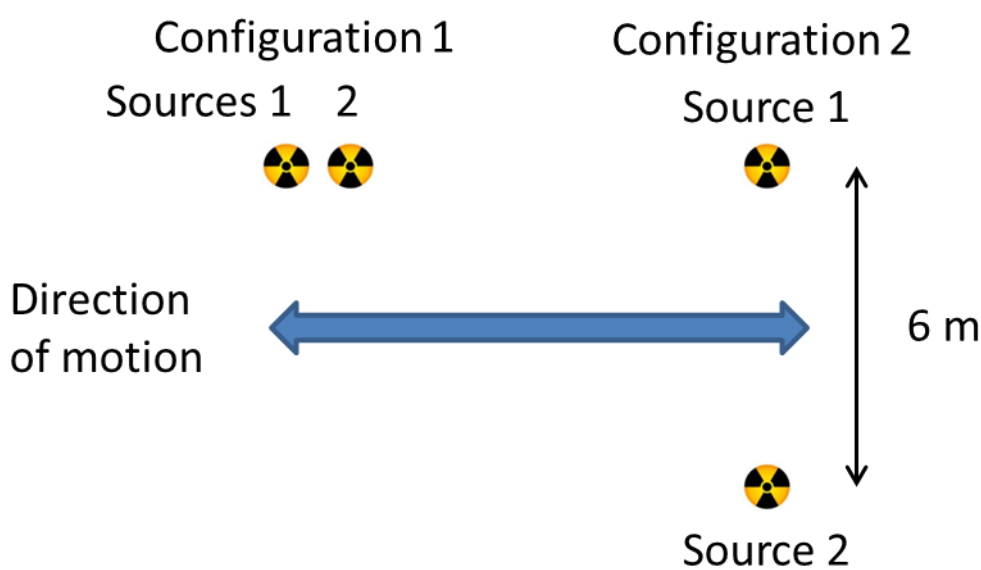

Figure 2: Source Configurations for Simultaneous Source Detection

Table 9: Summary of Source Configurations for Simultaneous Source Detection

Configuration	Source 1	Source 2
1	HEU or WGPu	simulated NORM, ^{60}C, ^{137}Cs, ^{192}Ir, ^{67}Ga, ^{99m}Tc, or ^{131}I
2	HEU or WGPu	simulated NORM, ^{60}C, ^{137}Cs,^{192}Ir, ^{67}Ga, ^{99m}Tc, or ^{131}I

6.4 False positive identifications produced by masking radionuclides

6.4.1 Requirement

The system shall correctly identify simulated NORM at the source to reference point distance that corresponds to the masking ratio of 5:1 for the WGPu target source fluence rate.

6.4.2 Test Method

For each test trial, the mobile system shall pass by the masking source (or source pass by the system) in the tested configuration corresponding to a masking ratio of 5:1, as defined in the requirements section, using the measurement parameters listed in Section 5.3. The WGPu target source is not used for this test. The test shall be carried out with the masking source placed at 0.5, 1.5, and 2.5 m from the floor or ground surface. Prior to each trial, ensure that the system background has been refreshed per manufacturer's instructions, if appropriate. The results from each series of tests for each configuration and test height are evaluated per Section 5.6.

6.5 Relative detection sensitivity at a fixed spherical radius characterization

6.5.1 Requirement

The system's response to ^{137}Cs and ^{252}Cf shall be characterized as a function of angle. The full-energy-peak efficiency shall be determined from each measurement position. Other sources, such as ^{57}Co and ^{60}Co, may be used in addition to the ^{137}Cs.

6.5.2 Test method

Following the measurement layout positions shown in Figure 3, determine the detector efficiency for each source. The starting height is 1.5 m (Z_0) from the ground surface or floor. The source activities shall be sufficient to keep the coefficient of variation from each measurement position at or less than 12%. For the neutron source it is acceptable to proceed if the coefficient of variation is greater than 12%.

1. Position the source at a radial distance of 3 m from the reference position as shown in Figure 3.
2. Obtain a series of 10 readings, calculate the mean, and determine the standard deviation.
3. Collect a spectrum.
4. Repeat the process at the next position.
5. Perform these measurements, except for step 3 for the neutron detector using a moderated neutron source (as defined in ANSI N42.43).

From the collected information, determine the system's efficiency for each source at each position.

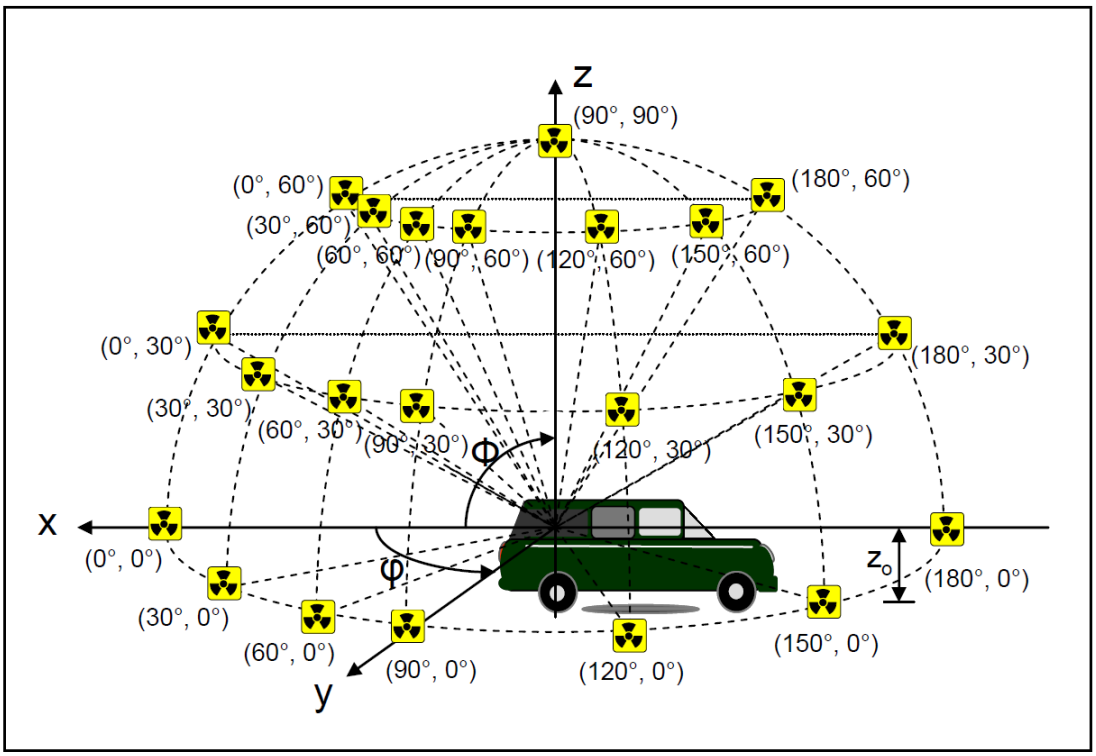

Figure 3: Source Location for Sensitivity Test

7 Documentation

No additional requirements.

Appendix A: Scoring definitions

Scoring is based on the DNDO scoring criteria. For this TCS, the alarm scoring logic listed in Table 10 shall be used.

Table 10: 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	Correct	Correct	False Negative
WGPu + simulated NORM	Correct	Correct	Correct	False Negative
DU + Simulated NORM	Correct	Correct	Correct	False Negative
No source	False Positive	False Positive	False Positive	Correct

The DNDO technical scoring logic for identification is employed by this TCS. Table 11 provides a summary of the Required Radionuclides (RRs) as well as the Additional Acceptable Radionuclides (AARs) for each test source.

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

- Category C3

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

- Category C4

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

If, without identifying the radionuclide of interest, the radiation detection system provides messages such as Unknown Source, Extras, Isotope not in library, Bad ID, Source not in library, Not in library, Gross counts, Reduced MDA, Reduced MDA for HEU, Reduced MDA for DU, Reduced MDA for WGPu, High Gamma, or Detection Compromise; then these messages shall be counted as FP5 (False Positive 5) and FP6 (False Positive 6) as described in the DNDO Scoring Logic document.

- Category FP5

The category FP5 means the 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 11: 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	None
^{192}Ir	^{192}Ir	None
WGPu	^{239}Pu	^{241}Pu, ^{240}Pu, ^{238}Pu, ^{241}Am, neutron, ^{237}U, ^{242}Pu, ^{233}U, Plutonium, Pu, WGPu
DU	^{238}U	^{235}U, ^{234}Pa^{m}, Uranium, DU
HEU	^{235}U	^{238}U, ^{234}Pa^{m}, 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, ^{234}Pa^{m}, HEU, Uranium, ^{60}Co
HEU + ^{137}Cs	^{235}U	^{238}U, ^{234}Pa^{m}, HEU, Uranium, ^{137}Cs
HEU + ^{192}Ir	^{235}U	^{238}U, ^{234}Pa^{m}, HEU, Uranium, ^{192}Ir
HEU + ^{99m}Tc	^{235}U	^{238}U, ^{234}Pa^{m}, ^{99}Mo, ^{99m}Tc, HEU, Uranium
HEU + ^{131}I	^{235}U	^{238}U, ^{234}Pa^{m}, ^{131}I, HEU, Uranium
HEU + ^{67}Ga	^{235}U	^{238}U, ^{234}Pa^{m}, ^{67}Ga, HEU, Uranium
HEU + Simulated NORM	^{235}U	^{232}Th, ^{226}Ra, ^{238}U, ^{234}Pa^{m}, 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, ^{234}Pa^{m}, Uranium, DU, ^{232}Th, ^{226}Ra, Thorium, Radium
No Source	None	None

Appendix B: NORM information

B1. Simulated NORM

A number of measurements were performed for different types of sands that could be used for NORM masking measurements. 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 test results are comparable when tests are performed at different facilities. 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 4 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 4, 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 5. 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).

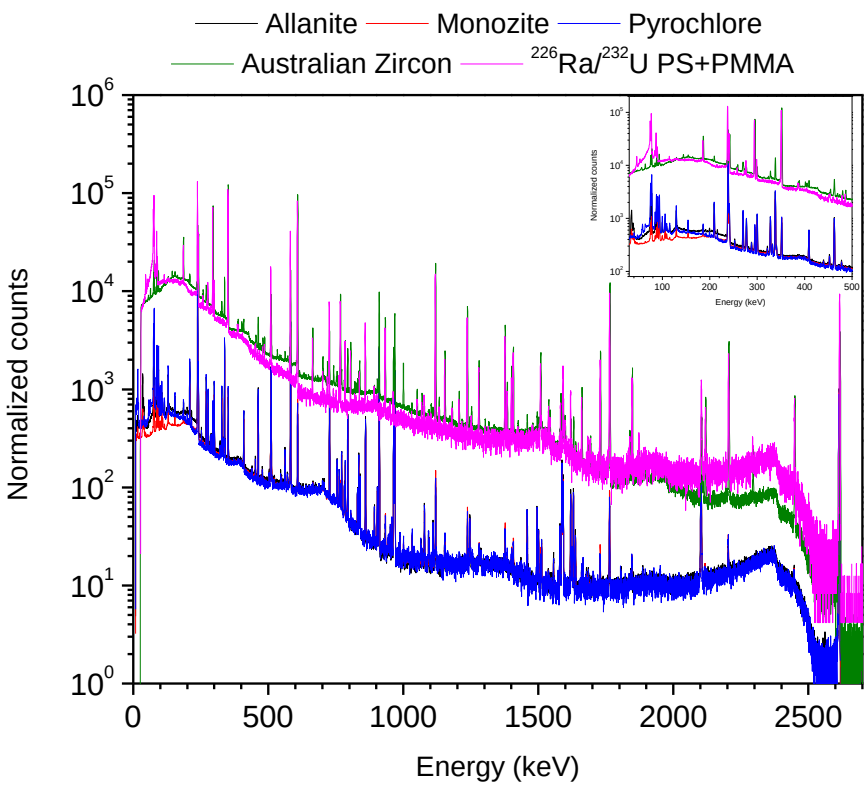

Figure 4: Spectra of Different NORM Samples and Simulated NORM Using ^{226}Ra and ^{232}U Point Sources Surrounded by 3.8 cm of PMMA

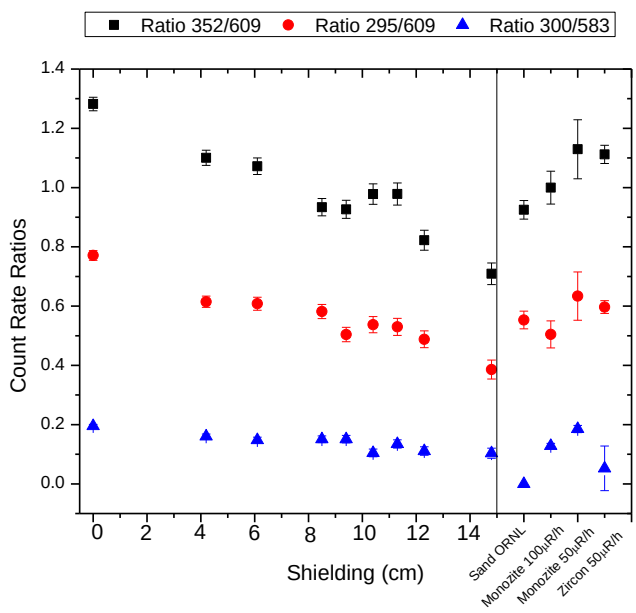

Figure 5: Ratios of Main Gamma-Ray Lines for the NORM and Point Sources Spectra. The Point Sources are Shielded with PMMA up to 15 cm Thick

B2. Masking ratios determination

During the development of the TCS for Radionuclide Identification Devices (RIDs), 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 (integrated 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 net peak area for HEU and WGPu sources when calculated using the total flux or region of interest were minimal as can be seen in Figures 6 and 7. The amount of HEU or WGPu needed to obtain the masking ratio using the total flux or the regions of interest is similar. Therefore, the TCS uses the total flux to determine the masking ratios.

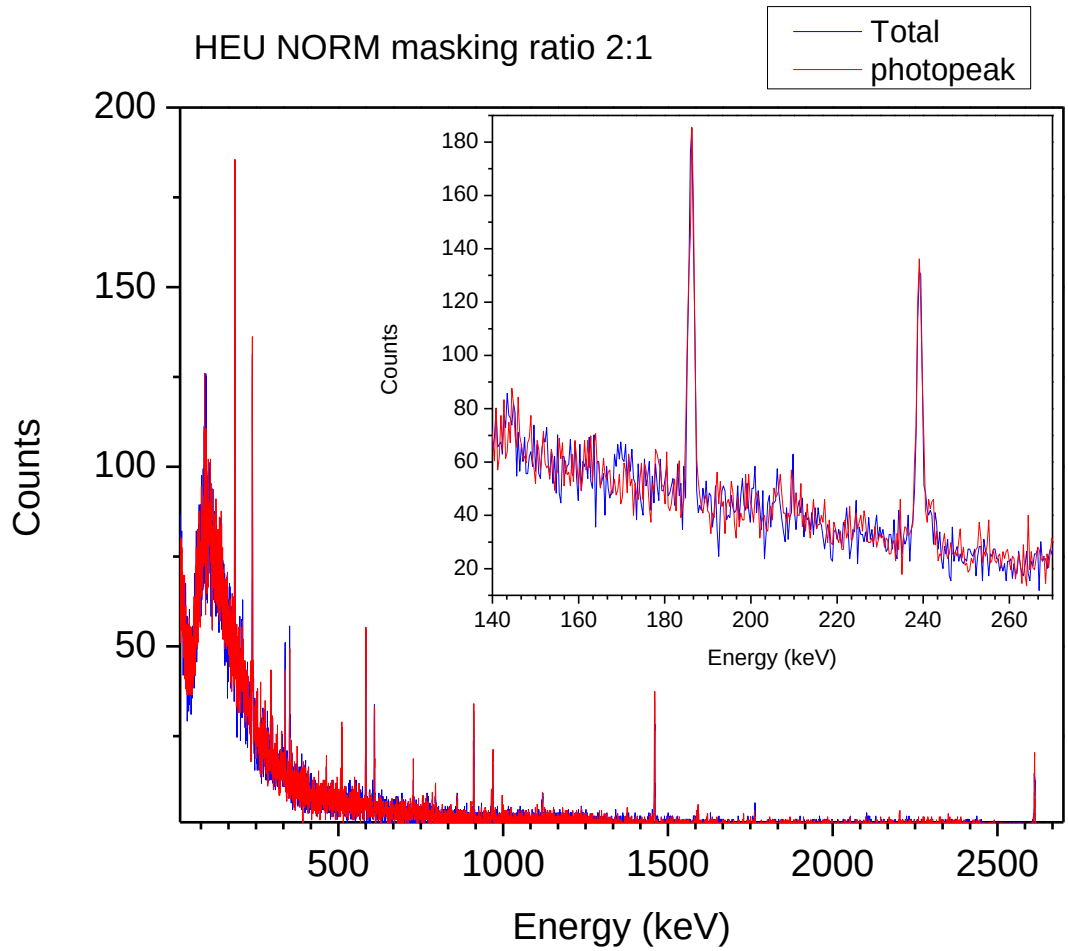

Figure 6: HPGe Spectra for HEU Source Masked with Sand
Masking Ratio Calculated Using Regions of Interest and Total Flux, Masking Ratio 2:1

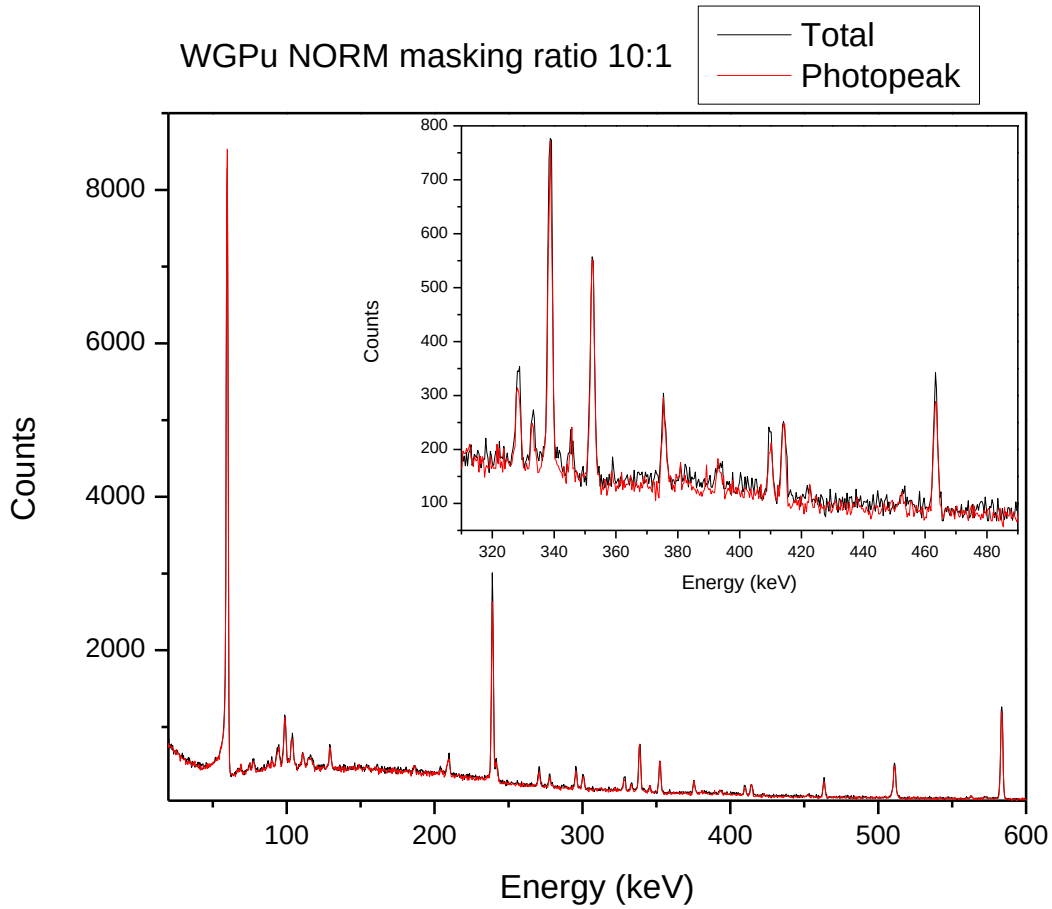

Figure 7: HPGe Spectra for WGPu Source Masked with Sand, Masking Ratio Calculated using Regions of Interest and Total Flux, Masking Ratio 10:1

Appendix C: Fluence rates

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, d*N*, that would cross an area, d*a*, 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.

$$\phi = \frac{\mathrm{d}N}{\mathrm{d}a} \qquad \text{(C.1)}$$

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

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

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.

C2. Determination of fluence rates for the SNM and DU sources

The fluence rates for the 1 kg HEU and 400 g WGPu spheres were determined using the Gamma Detector Response and Analysis Software (GADRAS). The DU values were obtained from measurements performed of a 2.5 kg DU plate.

In order to obtain the fluence rates an HPGe detector was calibrated using NIST traceable point sources placed at a distance of 1.5 m from the front face of the detector. The measured full-energy-peak efficiency is shown in Figure 8 together with the associated 6th degree polynomial fit. The acquired spectra from the point sources were used to obtain the detector response function in GADRAS.

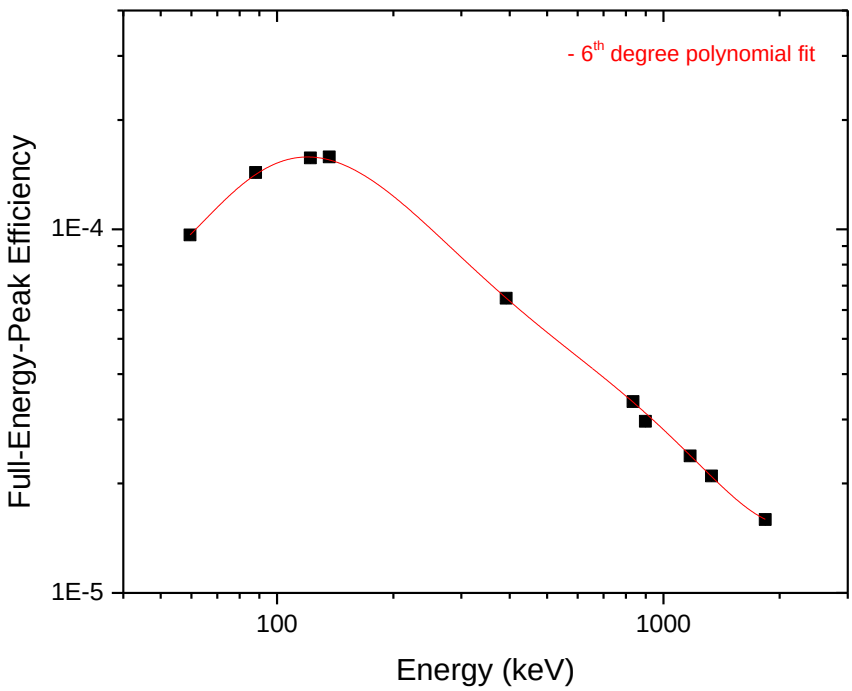

Figure 8: HPGe Detector Full-Energy-Peak Efficiency at 1.5 m

A spectrum of a (10 x 10 x 0.3175 cm) DU plate was measured 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 spectrum (see Figure 9). The count rate provided by GADRAS for the 1001 keV gamma-ray line was 1.3 cps for the measured spectrum and 1.4 cps for the calculated spectrum corresponding to an approximately 7 % difference between the measured and calculated values.

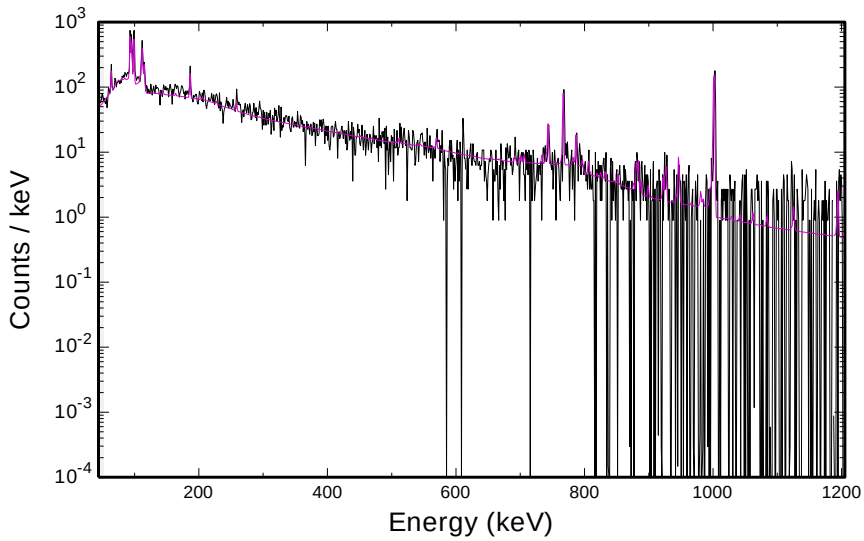

Figure 9: Measured and GADRAS Generated DU Plate Spectrum

The spectra for the 1 kg HEU and 400 g WGPu spheres were generated using the GADRAS 1-D model. The count rates from 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 then 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, $\varepsilon(E)$ 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 the DU plate are shown in Table 12.

Table 12: Summary of Fluence Rate Calculations

Source	Mass (g)	Emission rate[1] (photon/s)	R_{net}[1,2] (cps)	$\epsilon(E)$[2]	Distance (cm)	Fluence rate (photons/s/cm^2)*
HEU	1000 (Sphere)	4.70×10^5	16.5	3.50×10^{-5}	300	0.42
WGPu	400 (Sphere)	1.15×10^6	17.9	1.55×10^{-5}	300	1.02
DU	2500 (Plate surface area 400 cm^2)	1.71×10^5	1.20	6.99×10^{-6}	300	0.15

[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.
[2] The count rates and efficiencies are given at a distance of 3 m.
* The fluence rate estimated uncertainty is 9 % (1 standard deviation). Values are calculated at a distance of 3 m.

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 13.

Table 13: 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

C3. 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:

$$\dot{\phi} = \frac{Area_{net}}{T_{Live} * \epsilon(E) * 4\pi d^2} \qquad \text{(C.9)}$$

where $Area_{net}$ is the net photo-peak area (in counts) of the gamma line of energy *E*, $\varepsilon(E)$ 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.1].

References:

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