# Illicit Trafficking Radiation Assessment Program (ITRAP+10)

## Test campaign summary report

*January 25, 2016*

Homeland Security

European Commission

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Launched by the European Commission's Directorate-General for Home Affairs (DG HOME), the Illicit Trafficking Radiation Assessment Program (ITRAP+10) was implemented by the European Commission's Joint Research Centre (JRC) in close cooperation with the US Department of Homeland Security (DHS-DNDO) and contributions of the US Department of Energy (DoE) and the IAEA.

This summary report aims at making the results of the ITRAP+10 test campaign available to the international community. It includes an overview of the ITRAP+10 test program and a summary of results across the nine classes of instruments tested by the DHS-DNDO and the JRC. Moreover, it also takes into account the discussion of the standards used for testing and the feedback provided to the standards community to help with the standards' revisions.

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The ITRAP+10 summary report is also made available by the U.S. Department of Homeland Security – Domestic Nuclear Detection Office with the following identifiers:

Guidance: DHS SCG DNDO-001.1, 12/12

Document Number: 200-ITRAP-124860V1.0

# Table of Changes

The following table indicates the changes that were made to the document since its last release.

| New Version | Modified By | Section | Page | Changes Made |
| --- | --- | --- | --- | --- |
| 1.0 | | | | Initial Release |

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# Executive Summary

Nuclear terrorism is a global security challenge and cannot be addressed by any one nation alone. Overcoming this challenge requires strong regional and international cooperation. The United States and the European Commission, in cooperation with the International Atomic Energy Agency (IAEA), each understand the importance of nuclear security and embrace the shared international responsibility to develop and promote systems and measures for the prevention of, detection of, and response to nuclear or other radioactive materials out of regulatory control. Implementing effective capabilities to detect and intercept unauthorized movement of nuclear and other radioactive materials both at borders and within States adds to global defenses against nuclear terrorism. Often, these capabilities necessitate the use of technical instruments and sensors that can detect and identify nuclear or other radioactive materials so that they may be interdicted.

The Illicit Trafficking Radiation Assessment Program (ITRAP+10) is a program initiated by the European Union and the United States to evaluate the performance of available commercial radiation detection equipment against consensus standards. Through ITRAP+10, the international partners worked to ensure that testing standards are clearly defined, comprehensive and realistic in order to provide decision makers and private sector stakeholders with reliable detection system performance information as well as possible methods to enhance equipment performance. To ensure the review of commercial equipment would be relevant to the global commons, the European Commission Directorate General for Home Affairs (EC-HOME), the Joint Research Centre (EC-JRC), the U.S. Department of Homeland Security Domestic Nuclear Detection Office (DNDO), the U.S. Department of Energy (DOE), and the International Atomic Energy Agency (IAEA) agreed to collaborate on the conduct of the ITRAP+10 test campaign and share in the design of the tests, their execution, and the analysis of the data.

During ITRAP+10, commercial radiation detectors were tested against the American National Standards Institute/Institute of Electrical and Electronics Engineers (ANSI/IEEE) and the International Electrotechnical Commission (IEC) published consensus standards. These standards cover nine different classes of radiation detection instruments to include: Personal Radiation Detectors (PRDs), Spectroscopic Personal Radiation Detectors (SPRDs), Radionuclide Identification Devices (RIDs), Gamma Sensitive Detectors (GSDs), Neutron Sensitive Detectors (NSDs), Backpack-type Radiation Detectors (BRDs), Mobile Systems, Radiation Portal Monitors (RPMs) and Spectroscopic Radiation Portal Monitors (SRPMs). This report describes the results of the tests performed against the standards for these nine different classes of instruments.

Tests were conducted at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee, Pacific Northwest National Laboratory (PNNL) in Richland, Washington, Savannah River National Laboratory (SRNL) in Aiken, South Carolina, and the Joint Research Centre in Ispra, Italy from 2011 to 2014. Testing was performed against the standards and in accordance with applicable test protocols: general description, general requirements, radiological, environmental, electromagnetic, and mechanical tests. The environmental, electromagnetic, and mechanical tests were not performed for all the classes of instruments. General results from testing include observation of significant differences in performance among instruments of the same model. Across instrument classes, user manuals and documentation tend to be of poor quality. Instruments within some classes (e.g., Mobiles, SRPMs, GSDs) often performed at similar levels for a given test type (e.g., general, radiological), whereas, for other classes, a high degree of variability in performance among the instruments was observed (e.g., PRDs, RIDs, RPMs).

In addition to an overview of the main results from the ITRAP+10 program, this report also includes discussion of the standards used for testing. ITRAP+10 provided a forum in which to test the standards, and feedback was presented to the standards community to help with revisions. Although no instrument met all the requirements for a given standard (some met the requirements within a single test type), the results provide users with the knowledge of the instrument capabilities and limitations.

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# ITRAP+10 Summary Report

## 1 Introduction

Nuclear terrorism is a global security challenge and cannot be addressed by any one nation alone. Overcoming this challenge requires strong regional and international cooperation. The United States and the European Commission, in cooperation with the International Atomic Energy Agency (IAEA), each understand the importance of nuclear security and embrace the shared international responsibility to develop and promote systems and measures for the prevention of, detection of, and response to nuclear or other radioactive materials out of regulatory control. Implementing effective capabilities to detect and intercept unauthorized movement of nuclear and other radioactive materials both at borders and within States adds to global defenses against nuclear terrorism. Often, these capabilities necessitate the use of technical instruments and sensors that can detect and identify nuclear or other radioactive materials so that they may be interdicted.

The Illicit Trafficking Radiation Assessment Program (ITRAP+10) is a program initiated by the European Union and the United States to evaluate the performance of available commercial radiation detection instruments against consensus standards. To ensure the review of commercial instruments would be relevant to the global commons, the European Commission's Joint Research Centre (EC JRC), the Domestic Nuclear Detection Office (DNDO), the U.S. Department of Energy (DOE), and the International Atomic Energy Agency (IAEA) agreed to collaborate on the conduct of the ITRAP+10 test campaign and share in the design of the tests, their execution, and the analysis of the data. The results provide an independent assessment of radiation detection instruments that is presently available on the market, or soon will be. The goal of the test campaign is to provide the best test data available to assist stakeholders in effectively detecting radioactive materials crossing borders illegally (whether importations, exportations, or shipments in transit) by developing recommendations that describe the technical and functional requirements for the selection of radiation detection instruments so that resources are deployed in an efficient way.

The purpose of this report is to:

- Provide background information about the ITRAP+10 program.
- Describe the types of systems tested.
- Provide a description of ITRAP+10 test locations and basic data analysis.
- Provide information about how to get more detailed test reports.
- Describe the relevant consensus standards and conformity test processes.
- Provide a general summary of the outcomes of ITRAP+10, including lessons learned and recommendations based on the testing process and test results.
- Provide a list of participating manufacturers.
- Provided an overall summary of test results for the different classes of instruments tested.

## 1.1 Instruments Used For Nuclear Security

Different types of instruments are procured, deployed, and used by law enforcement or technical experts at various points of entries (POEs), stations, and sites. The predominant radiation detection technologies deployed today are listed below:

- Personal Radiation Detectors (PRDs) are pocket-sized and body-worn instruments. They are used as scanning tools to detect and localize nuclear and radiological materials, based on gross count measurements, in support of the nuclear detection mission. Most PRDs can display exposure rates. Newer versions of these devices provide spectroscopic capabilities suitable for the identification of some nuclear and radioactive materials (SPRDs).
- Gamma Search Detectors (GSDs) and Neutron Search Detectors (NSDs), are hand-held type instruments that are designed for search and detection of radioactive materials based on gross counts. Some GSDs have the capability of categorizing radionuclides.
- Hand-held Radionuclide Identification Devices (RIDs) are designed to identify the radionuclides present in radioactive materials and sources. These instruments are normally used as a secondary tool after a source was detected by a gross counting instrument.
- Backpack Radiation Detectors (BRDs) are body-worn instruments, typically capable of detecting both gamma and neutron radiation. These may also include the ability to identify specific isotopes. Such systems may be used in either discrete or overt operational deployments generally to help search for radioactive materials.
- Mobile systems generally are used for detection and identification while moving, either mounted in a vehicle, trailer or other transportable form-factor. They can be used for area surveillance, search, or as temporary static portal monitors. They often use large volume gamma and neutron detectors.
- Radiation Portal Monitors (RPMs) are large in size, permanently installed, and usually used in border crossings and POEs. By virtue of their size, these devices are much more sensitive to gammas and neutrons compared to hand-held instruments. Newer versions of portal monitors, containing sodium iodide (NaI) or high-purity germanium (HPGe) detectors, also provide nuclide identification capabilities (SRPMs).

## 1.2 Test Locations, and Data Analysis

The tests were conducted at Oak Ridge National Laboratory (ORNL), in Oak Ridge, Tennessee, Pacific Northwest National Laboratory (PNNL), in Richland, Washington, Savannah River National Laboratory (SRNL), in Aiken, South Carolina, and at the JRC, in Ispra, Italy. The data was validated and verified by the different laboratories as well as by the Johns Hopkins University/Applied Physics Laboratory. The data was analyzed and reports were written by different laboratories including the National Institute of Standards and Technology (NIST), Lawrence Livermore National Laboratory (LLNL), Argonne National Laboratory (ANL), DNDO, and the JRC. Because of the difference in availability of radiological sources at the JRC and the respective U.S. testing facilities, some source substitutions were necessary. In addition, the European and American laboratories sometimes differed in their interpretations of test methods and performed slightly different measurements.

## 1.3 ITRAP+10 Reports

Several different types of reports were written, these included vendor reports, summary reports and comprehensive reports. The vendor reports summarize the test results for each instrument (provide detailed information about each test performed), the summary reports list the main results of the test and the comprehensive reports combine the US and JRC test results, see the list of references for a list of reports.

For each instrument tested, a report was written summarizing the results of the tests. These reports were provided to the instrument manufacturers and are available for distribution to government entities or upon request to the JRC and DHS DNDO (references [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]).

## 1.4 Standards Used for Testing

During ITRAP+10, commercial radiation detection instruments were tested against the American National Standards Institute/Institute of Electrical and Electronics Engineers (ANSI/IEEE) and the International Electrotechnical Commission (IEC) published consensus standards. These standards cover nine different classes of radiation detection instruments to include: Personal Radiation Detectors (PRDs), Spectroscopic Personal Radiation Detectors (SPRDs), Radionuclide Identification Detectors (RIDs), Gamma Search Devices (GSDs), Neutron Search Devices (NSDs), Backpack-type Radiation Detectors (BRDs), Mobile Systems, Radiation Portal Monitors (RPMs) and Spectroscopic Radiation Portal Monitors (SRPMs). This report describes the results of the tests performed against the standards for these nine different classes of instruments. The number of instrument models tested within each class varied widely, with the PRDs and RIDs having the largest number of instrument models. This is a reflection of the classes of instruments that are predominantly used in the field as well as the level of maturity of the technology. In addition, the number of tests described in each of the standards vary depending on the instrument's capabilities. For example, a RID can detect gamma and neutron radiation, can provide an estimate of the exposure or ambient dose equivalent rate produced by a radioactive source, can localize a source, and identify the radionuclides present in source; a NSD can usually only detect neutron radiation. Therefore, many more tests are required to evaluate the performance of some instrument classes compared to others.

Standards are important because they provide safety and reliability in a product, raising user confidence in the performance of instruments. They support government policies and legislation, allow for interoperability of devices, and provide a foundation for the development of new features and options required by consumers. Businesses and manufacturing also benefit from standards as they allow them to develop new technologies, enhance existing practices, open up market access, encourage innovation, and increase awareness of technical developments. Consensus standards require agreement between involved parties as to the content in the standard and are developed in a collaborative manner. The involved parties include manufacturers, users, and experts in specifics areas addressed by the standards and testing laboratories. Consensus standards are used in a wide variety of conformity assessments programs.

Conformity assessment procedures provide a means of ensuring that the products, services, systems, persons, or bodies have certain required characteristics, and that these characteristics are consistent from product to product, service to service, system to system. Conformity assessment can include: supplier's declaration of conformity, sampling and testing, inspection, certification, management system assessment and registration, the accreditation of the competence of those activities, and recognition of an accreditation program's capability. Together standards and conformity assessment activities impact almost every aspect of life worldwide. Conformity assessment activities can be performed by many types of organizations or individuals. Conformity assessment can be conducted by: (1) a first party, which is generally the supplier or manufacturer; (2) a second party, which is generally the purchaser or user of the product; (3) a third party, which is an independent entity that is generally distinct from the first or second party and has no interest in transactions between the two parties; and (4) the government, which has a unique role in conformity assessment activities related to regulatory requirements.

ITRAP+10 provides the opportunity for the test community to ensure that standards are clearly defined, comprehensive, and realistic. The international collaboration aspects of this program may also help realize greater homogeneity in international and American standards for radiation detection instruments. In addition, ITRAP+10 will help industry better understand how available detection instruments performs and drive industry to pursue advances that will ultimately improve radiological and nuclear detection capability.

Individual standards were written for the different types of commercially available radiation detection instruments. Therefore, each standard may have different requirements depending on the instrument type and its intended use. Testing of the radiation detection instruments was based on the following American National Standards Institute/ Institute of Electrical and Electronics Engineers (ANSI/IEEE) and the International Electrotechnical Commission (IEC) standards requirements:

- Personal Radiation Detectors (PRDs) - ANSI/IEEE N42.32 [18] and IEC 62401 [19].
- Spectroscopic Personal Radiation Detectors (SPRDs) - ANSI/IEEE N42.48 [20] and IEC 62618 [21].
- Gamma Search Detectors (GSDs) - ANSI/IEEE N42.33 [22] and IEC 62533 [23].
- Neutron Search Detectors (NSDs) - IEC 62534 [24].
- Radionuclide Identification Devices (RIDs) - ANSI/IEEE N42.34 [25] and IEC 62327 [26].
- Backpack-type Radiation Detectors (BRDs) - ANSI/IEEE N42.53 [27].
- Mobile Systems - ANSI/IEEE N42.43 [28].
- Radiation Portal Monitors (RPMs) - ANSI/IEEE N42.35 [29] and IEC 62244 [30].
- Spectroscopic Radiation Portal Monitors (SRPMs) - ANSI/IEEE N42.38 [31] and IEC 62484 [32].

## 1.5 Correlation between Field Operations and Standards Requirements

The operational condition under which the different types of instruments are used in the field are translated into specific requirements in the standards. Below are some examples of the correlation between the field operation needs and the standards requirements:

**False alarm rate**

One of the main requirements of the users is having an instrument with a low false alarm rate, as they do not want to spend their resources responding to instrument's alarms when no radioactive sources are present. Users tend to get desensitized to an instrument that has a high rate of false alarms. This need translates to the false alarm rate requirement that depends on the type of application or deployment.

### Time to alarm

For the hand-held and body-worn type instruments, users may need to scan a crowd of people to determine if a person is carrying a source. The goal is to find and/or stop the right person. This situation translates to the time to alarm test described in the standards. In most standards, the instrument is required to alarm within 2 seconds of being exposed to the source. Depending on the size of the crowd and/or the walking speed of the people, the user should not stop the person closest to him or her but rather should stop the group of nearest people. The size of the group depends on the sensitivity of the instrument. Similarly, if the instrument is used to scan a vehicle, the time to alarm provides information to the user about how far the source can be from the instrument at the time of alarm.

### Over-range indication

For the personal protection of the user to a high radiation field, the over-range test requirement is specified in the standard to ensure that the instrument readings do not drop to zero and/or saturate in a high field and to inform the user to leave a potentially high radiation field. In an over-range condition, the instrument response is no longer reliable. Most manufacturers state in the documentation the field strengths over which the instruments are in over-range conditions. Some instruments do provide the operator with an indication that the instruments are in too strong a field. Whether the instrument is equipped with this feature or not, the instrument should still remain in an alarm state, as it is in a radiological field, and not to be so saturated that it stops working and alarming.

### Neutron indication in the presence of photons

In the field, the operational response to a neutron alarm is more severe because of the few real neutron sources and their association with SNMs. Some neutron detectors are also sensitive to high gamma radiation fields. It is important that high gamma radiation fields, such as those produced by sources similar to those encountered in medical patients, do not trigger a neutron alarm. The neutron alarms in the presence of photons test in the standards is designed to address this issue.

### Accuracy test

Some users may want to have a rough idea of the dose being received or may want to use some types of instruments to setup a barrier where the radiation field has a specific value. The accuracy test requirements specified in the standards help address these issues.

### Environment

Users may need to know under which normally encountered weather conditions the instrument still works as expected. For example, if an instrument is deployed in a cold weather environment, it is important to know if the instrument's detectors and display will be operational. The environmental tests in the standards provide this type of information. The standards include tests such as temperature, humidity, moisture, and dust to assess the instrument's performance under different environmental conditions.

### Radio frequency

Many users carry or work close to other electronic devices (e.g., cell phones, radios, radars) that may affect the response of the radiation detection instruments. The radio frequency (RF) test in the standards provides users with information about the susceptibilities of the radiation detection instruments to electromagnetic radiation from nearby electronic devices. For example, for the PRDs the requirements for the RF test were set because PRDs were alarming when users' cell phones were about to receive a call, and users did not want to have the PRDs alarming under those circumstances.

**Radiated emissions**

As mentioned previously, many users carry or work close to other electronic devices, so it is important that the radiation detection instruments do not emit electromagnetic radiation that may interfere with the operation of those electronic devices. The radiated emissions test described in the standards helps to verify that the radiation detection instruments do not interfere with other electronic devices.

**Electrostatic discharge**

When working in dry weather conditions, it is common for people to produce a spark generated by an electrostatic discharge when touching certain types of surfaces. The electrostatic discharge test requirements in the standards is designed to verify that the instrument still works after being exposed to such a spark.

**Battery life**

For certain types of instruments, many users cannot afford to recharge or change batteries in the middle of a working shift. The battery life-time requirement in the standards helps to verify the duration of batteries under certain operational conditions.

**Magnetic field**

Some engines or high-power machinery may produce magnetic fields that can affect the instrument response when users get close to these fields. Magnetic fields tend to affect instruments with radionuclide identification capabilities if they are not properly shielded. The requirements specified in the standards address this type of scenario.

**Vibration**

Many users carry their instruments inside a vehicle prior to use, or they might have an instrument that is being used to measure radiation levels in a specific location while mounted inside a vehicle. For these cases, vibration tests may try to simulate having an instrument in a car being driven on a rough road. Mechanical vibration can produce a spurious alarm that is not due to the presence of radioactive materials. If such an alarm exists, users may not be able to distinguish it from the presence of a radioactive source. For these types of scenarios, the vibration test requirements are specified in the different standards.

**Impact**

Instruments are commonly bumped against surfaces while in use, so to assess the instrument response under those circumstances, the standards have specific requirements for the impact test. As with the mechanical vibrations, impacts can also produce spurious alarms that are not due to the presence of radioactive materials.

**Drop test**

Due to the variety of duties that users may carry out while carrying or using a radiation detection instrument, there is a high chance that the instruments will be dropped, so it is important that the instruments do not break when dropped. The drop test requirements specified in the standards are designed to address such need.

## 1.6 Outcomes from ITRAP+10

The testing process as well as the test results obtained during ITRAP+10 helped:

- Revise both the requirements and test methods described in the standards
- Increase the capabilities of the testing laboratories
- Manufacturers improve their products
- Users understand the performance and limitations of the currently available radiation detection instruments

**Revision of standards**

After the ITRAP+10 testing was completed, several ANSI/IEEE and IEC consensus standards were revised to address the issues encountered during testing. The main change included the addition of more detailed test methods to assists the testing laboratories in test procedures and to ensure that different laboratories perform the tests in the same way. In addition, more information about test setup tolerances, uncertainties, and statistical methods were included based on comments and observations from the testing laboratories. The ITRAP+10 effort accentuated the need to validate the standards' requirement and test methods prior to their publication. A few requirements and test methods were changed to address the current technical capabilities of the instruments available in the market. When performing the pre-test and post-test measurements for the environmental, mechanical, and electromagnetic tests it was found that it is important to have a reproducible radiation field and to ensure the statistical variation in the instruments' readings is kept as small as possible, reducing the probability of rejecting a good instrument.

**Increase capabilities of laboratories**

During the ITRAP+10 testing, the laboratories refined their procedures and upgraded their testing equipment. In several laboratories, new acquisition systems were developed to address the high throughput of data generated by the large number of instruments tested. Novel visual and vibration sensors were used to capture the response of the different instruments, reducing the data analysis time that was spent reviewing videos that were previously used to capture the instrument response. New source irradiators were designed to allow testing the instruments as described in the standards [33]. The ITRAP+10 effort accentuated the need to have accredited testing laboratories and proficiency tests to compare the laboratory capabilities to perform testing against the consensus standards in order to have reproducible test results, independent of testing location.

**Improved manufacturers' products**

Manufacturers can benefit from the ITRAP+10 results as they provide information about the current level of performance of their instruments and show the areas in which improvements are needed in order to meet the standards requirements. Some of the issues can be easily addressed, for example, the revision of the instruments' manuals in order to meet most of the general and documentation requirements. Another important piece of information is the potential need to increase the instruments' ruggedness, so they can operate in the required environmental, mechanical, and electromagnetic field conditions. Knowing the probability of detection and/or identification of the different instruments can help manufacturers improve their algorithms as well as hardware.

**Improve users knowledge of instrument performance and availability**

Even if no single instrument meets all the standards' requirements, users can make use of the ITRAP+10 results to understand the limitations of the different instruments and develop their operating procedures to effectively use their instruments and detect radioactive materials. Operating procedures can be developed to circumvent some limitations of the instruments. When making procurement decisions, the test results can help the user decide on which instrument type and model is better suited for their application. Not all applications require the use of an instrument that meets all the requirements listed in the standards.

## 1.7 Constraints and Limitations

### 1.7.1 Constraints

- The scope of the tests was constrained by resources. The JRC tested based on standards while DNDO tested according to standards, and as a result some of the tests in the standards were not performed, based on the availability or resources.
- Based on the available resources, test configurations were not always identical between test facilities. For example, source strengths or radionuclides were sometimes different.
- Manufacturer participated on a voluntary basis. Instrument settings were setup by the manufacturer prior to testing. For small instruments, three units of a given model were requested. In some cases, the manufacturers could provide only one or two units per model. For larger instruments, only one unit of a given model was provided.

### 1.7.2 Limitations

- It is expected that manufacturers improved their instruments based on the results of the tests. Therefore, instruments in the market today may not have the same performance as those tested by ITRAP+10.
- Any procurement effort should not use ITRAP+10 results as the sole source of technical and scientific information.

## 1.8 Participating Manufacturers

In all, 79 models of instruments, supplied by 24 manufacturers world-wide, were tested by the ITRAP+10 collaboration. Some of the models were tested concurrently by the JRC and by DNDO to ensure consistency of results. The instruments are described in detail in each of the results sections. The list of vendors, along with their contact information is provided in Appendix C.

## 1.9 Summary of Test Results

The general observations for the different instrument classes are summarized below. Section 2 provides more complete summaries of the test results. For large size instruments, only one unit per model was tested.

For small size instruments, three units of a given instrument model were tested for most models, although in some cases fewer units were tested. It is worth noting that for some of the instrument models, the behavior of the different units was not always consistent. In some instances, it was observed that one unit behaved significantly worse or better than the other units.

**PRDs**

*General Requirements*

Fourteen PRD models were tested. Seven were equipped with neutron detectors. Most PRDs had a back-light LCD display and could either display exposure or ambient dose equivalent rate. Two of the PRDs had a unit-less LED display, and a conversion table was provided to translate the displayed values to exposure or ambient dose equivalent rate. All PRDs were equipped with visual, audible, and vibrational alarms. Most PRDs used non-rechargeable batteries. Only two PRDs were certified for use in explosive atmospheres.

*Radiological Tests*

For most PRDs, the alarm threshold was set when the instrument was powered on, based on the measurement of background radiation. Most PRDs displayed less than 1 false alarm in 10 hours. Overall, most of the PRDs detected gammas in less than 2 seconds for the three sources used in the test at two different background radiation levels. For most PRDs, the ambient dose equivalent rate readings were accurate for medium-energy gamma-ray type sources, but most were outside the standards requirements for low-energy gamma-ray and high-energy gamma-ray sources. All PRDs displayed an over-range indication, and eight were equipped with personal protection alarms. Most PRDs that claimed neutron detection capabilities did not detect the presence of a neutron source, and the time to alarm was larger than required by the standards. Two of the PRDs did not indicate neutrons when exposed to a high-energy gamma-ray radiation field meeting the standards requirements.

*Environmental, Electromagnetic, and Mechanical Tests*

Most PRDs had problems operating at +50°C. When the PRDs were moved from room temperature to +50°C, most worked correctly for the first 15 minutes but their performance degraded over time. Most PRDs were impenetrable to dust. Most PRDs were not water sealed, as evidenced by water penetrated during the test, though in several cases the PRDs continued to function as they dried. One PRD was not susceptible to radio frequency interferences, but all other PRDs were susceptible (though to different frequencies). The PRDs did not produce radiated emissions that could interfere with the operations on neighboring devices. Most PRDs were affected by the vibration test. Several PRDs were not damaged by the drop test and most were not susceptible to mechanical impacts.

**SPRDs**

*General Requirements*

A total of six models of SPRDs were tested. Overall these instruments met the general requirements in the standards, with the exception of battery lifetime.

*Radiological Tests*

Most SPRDs detected gammas in less than 3 seconds and neutrons in less than 5 seconds. For most SPRDs the ambient dose equivalent rate readings were accurate for medium- and high-energy gamma-ray type sources, but all were outside the standards requirements for low-energy gamma-ray source. Almost every instrument performed well on identification of single radionuclides and reasonably well at identifying two radionuclides simultaneously. Many were able to identify a radionuclide "masked" by the field of another.

*Environmental, Electromagnetic, and Mechanical Tests*

The gamma response and identification was stable across a wide range of temperatures and humidities for most SPRDs; neutron response was more mixed. Results were similar for the electromagnetic interference tests. Most of the instruments did well in the mechanical tests, except for the drop test – only one instrument was undamaged. Two of the five instruments tested were damaged in the impact test.

**GSDs**

*General Requirements*

Four GSDs were tested. Overall these instruments met the general requirements in the standards.

*Radiological Tests*

Most GSDs were quick to detect a gamma source, provided accurate ambient dose equivalent rate readings, and had very low false alarm rates.

*Environmental, Electromagnetic, and Mechanical Tests*

Only two of the instruments were tested. They operated correctly in a wide range of temperatures and humidities. They were unaffected by different electromagnetic environments, though they displayed slightly less accurate performance in DC magnetic fields than in AC fields. Both GSDs emerged functional from the mechanical tests.

**NSDs**

*General Requirements*

A total of four NSDs were tested. All but one was equipped with a personal protection alarm. For the units for which battery performance was tested, the instruments were able to operate in a non-alarming state for well over 8 hours, and had stable sensitivity after 8 hours of operation. The batteries lasted for more than 3 hours, even in an alarming state for those instruments with alarms.

*Radiological Tests*

Only half of the instruments responded properly to neutrons in a mixed neutron/gamma field. Three of the four instruments responded noticeably to neutron sources.

*Environmental, Electromagnetic, and Mechanical Tests*

Only two of the instruments were tested. One operated well in temperature tests. This instrument was sensitive to electromagnetic interference. It operated correctly for almost all of the mechanical test except for the drop test. Statistical fluctuations on the other instrument made it difficult to determine sensitivity to environmental, electromagnetic, and mechanical effects.

**RIDs**

*General Requirements*

Sixteen RID models were tested, and fourteen provided a neutron indication. All RIDs were equipped with a personal protection alarm and had a visual and an audible indication. For most RIDs, the alarm could not be acknowledged unless the radiation source was removed, which is a desirable feature for the user protection.

*Radiological Tests*

Most RIDs detected the mid gamma-ray energy sources, most alarmed in less than 3 seconds. When exposed to a high gamma radiation field, eight of the neutron detectors did not produce a neutron alarm as required by the standards. Most RIDs detected a moderated neutron source, with the time to alarm varying between 1 and 24 seconds. Many of the RIDs did not detect an unmoderated neutron source. For all but three of the RIDs, the exposure or ambient dose equivalent rate readings for mid and high gamma-ray energy sources were within the required values. The exposure or ambient dose equivalent rate reading for low gamma-ray energy sources tend to be lower than the reference value for most RIDs. The RIDs did not display a specific over-range indication, instead they displayed different messages such as: "danger", "warning high ambient dose equivalent rate", "move back", "gamma detector saturated due to high count rate". When performing an identification of background, all except three of the RIDs, identified NORM or no radionuclides. Most RIDs could correctly identify the industrial, NORM, and HEU sources, though most of them have problems identifying WGPu and medical sources. In some cases, the probability of identification of shielded materials was better than that associated with bare sources. Four of the RIDs show a good identification performance against mixed gamma sources and masking test cases.

*Environmental, Electromagnetic, and Mechanical Tests*

Most RIDs worked properly over the entire temperature range, but a few had problems operating at low temperatures. During the temperature shock test, most RIDs worked correctly for the first 15 minutes, but the identification performance degraded with time. Most RIDs showed no dust or water penetration. Several RIDs were not susceptible to radio frequency interferences. Half of the RIDs did not produce radiated emissions that could interfere with the operations of neighboring devices. In general, RIDs were affected by DC magnetic fields. Most RIDs were affected by the vibration and mechanical tests. Few RIDs were not damaged by the drop test. Most were not affected by the mechanical impacts.

**BRDs**

*General Requirements*

Seven BRD models were tested. All could detect gamma and neutron radiation, and some could identify the radionuclides to which they were exposed. Some BRDs were equipped with a global positioning system (GPS) as part of the source localization capability. Except for one, all use rechargeable batteries. For most, the battery lifetime was over 8 hours.

*Radiological Tests*

Some displayed a large false alarm rate, though five displayed less than 5 false alarm in 10 hours. All BRDs, except for two, had problems detecting low gamma-ray energy sources. Most were able to detect all the other sources, and the time to alarm was less than 2 seconds with few exceptions. All but one of the BRDs tested by DNDO were unable to reliably detect both moderated and unmoderated neutron sources. The BRDs tested at the JRC produced more neutron detections for both moderated and unmoderated neutron sources, and most detected in more than 5 seconds. Only two models had a personal protection alarm. Three provided an over-range indication that worked as required by the standard. Most BRDs did not produce neutron detections due to the presence of an intense gamma radiation field.

*Environmental, Electromagnetic, and Mechanical Tests*

The BRDs did not work as expected for the entire temperature range, though they worked correctly for the entire humidity test. The radiated emissions were below the levels that could affect the operation of neighboring electronic devices. The two BRDs tested were susceptible to radio frequency interferences. One was not damaged due to the drop test. The vibration test affected one of the BRDs.

**Mobile Systems**

*General Requirements*

A total of four Mobile Systems were tested. Across all Mobile Systems, differences arose between event files stored on disk and the data observed by an operator from the graphical user interface.

*Radiological Tests*

Each Mobile System had a low false alarm rate over a period of three hours. One Mobile System, in particular, performed exceptionally well in detection and identification capabilities, whereas the others struggled. Probability of detection or identification was markedly higher with the sources stationary and in front of the respective instrument.

*Environmental, Electromagnetic, and Mechanical Tests*

The responses of the instruments were affected by changing environmental, electromagnetic, and mechanical parameters.

**RPMs**

*General Requirements*

Ten RPMs were tested, and eight were instrumented with neutron detectors. The data format of most RPMs did not comply with the ANSI N42.42 standard [34].

*Radiological Tests*

The rate of false alarms was generally low, especially for false neutron alarms. Most RPMs met the gamma detection requirement in greater than 70 % of all the height-source configurations (i.e., low, middle and top). This increased to nearly 100 % for configurations with an unmoderated neutron source (excluding the top height for some instruments). The detection probability decreased significantly for moderated neutron sources, which may indicate over-moderation of the neutron detectors in the RPMs themselves. Over-range indications were available in only half of the instruments.

*Environmental, Electromagnetic, and Mechanical Tests*

Performance in differing environmental, mechanical, and electromagnetic conditions was generally mixed, though many instruments were not tested due to their size. Tests that did not cause the instruments much trouble include dust, moisture, microphonics impact, and radio frequency interference.

## SRPMs

*General Requirements*

A total of seven SRPMs were tested, and six were equipped with neutron detectors. One of the largest problems with this class of instruments was the lack of consistency in alarm colors and inadequate operation manuals. Less than half of the SRPMs provided a specific over-range condition to alert users to potentially dangerous radiation levels. For some instruments, data observed by the operators did not agree with data from the recorded event files stored on disk.

*Radiological Tests*

Overall, the false alarm rate was low, and the systems had a high probability of detection for SNM sources. The detection probability for other gamma radiation sources varied quite a bit among instruments, with approximately half of the instruments detecting a multitude of sources at all heights (i.e., low, middle and top). For the other instruments, probability of detection was generally higher at the middle height. Neutron detection probability was nearly twice as high for unmoderated sources compared to moderated sources, as most SRPMs included internal moderators that surrounded the neutron sensors. This may be an indication of over-moderation.

Identification probability of SNM sources was mixed among instruments, though tended to increase if sources were stationary. When tested alone or simultaneously with other radiation sources, HEU was more successfully identified than WGPu, though this may be attributable to the higher strength of the HEU sources. The instruments identified industrial and NORM sources with a high frequency but experienced difficulties with medical sources. As observed with the SNM sources, testing with sources stationary in front of each instrument often increased the identification probability compared to passing the sources by at a fixed speed, although some SRPMs identified additional radionuclides in the stationary cases.

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# 2 Test Results

The testing was performed for the following sections of the standards for all the different classes of instruments: general description, general requirements tests, and radiological tests. The environmental, electromagnetic, and mechanical tests were not performed for all classes of instruments because of funding and availability of testing equipment for large instruments. In some cases, the manufacturer opted not to participate in a particular test. The JRC did not perform non-radiological tests. The instruments were setup according to the manufacturers specifications.

In general, radiological testing was performed in two modes: static and dynamic. In the static mode, the radiation source was placed at a fixed stationary distance in front of the instrument under test for a fixed time duration. In the dynamic mode, the source passed by the instrument at a fixed speed produced by a linear motion system. The duration and speed parameters were determined by the instrument class and type of instrument (e.g., vehicle or pedestrian portal monitor) as described by the standards. Some of the radiological tests for the RPMs, SRPMs, and Mobile systems, were performed by placing the sources at multiple heights (i.e., low, middle and top).

For the spectroscopic instrument classes, the devices not only detect the presence of radioactive sources (triggering an alarm) but also identify the specific radionuclide. It is possible for these instruments to detect without identifying the source. Some instruments also identify sources without detecting, depending on their alarm logic. Therefore, the probability to alarm is not always equal to the probability to identify.

The following is a general description for the radiological tests performed:

- False alarm: In a stable background condition, the instrument was monitored for alarms over a period of time or for a given number of occupancies.
- Time to alarm: Measures the time for the instrument to respond to low-, medium-, high-energy gamma sources as well as neutron sources. The sources were moved at specific speeds depending on the type of instrument. In some cases, the sources were popped-up in front of the instrument.
- Response to gammas/neutrons: Several sources including low-, medium-, high-energy gamma, HEU-like, WGPu-like, NORM and neutron sources (depending on the type of instrument) were detected by the instruments. The tests were performed in the dynamic and/or static modes and at different heights.
- Accuracy: Compares the radiation field as measured by the instruments with a reference value. Accuracy was tested independently with three different radionuclides producing low-, medium-, and high-energy gamma radiation. For each radionuclide, tests were conducted at several intensities covering several orders of magnitude in exposure rate or ambient dose equivalent rate readings.
- Over-range: The instruments were exposed to the medium-energy gamma source at a radiation field that was above the maximum range of the instrument to determine if the instrument displayed an over-range indication and if the instrument readings drop to zero and/or saturate.
- Neutron indication in the presence of photons: Without a neutron source present, the instruments were exposed to a medium-, and/or high-energy gamma source at a high radiation field to verify that a neutron alarm was not triggered. In addition, for some instruments, it was verified that the neutron source was detected while the gamma source was present.

- Radionuclide identification: The instruments were exposed to different radioactive sources to determine if they were correctly identified. These included SNM, industrial, medical, and NORM sources. Some tests were performed with single sources and with two (or more) sources together. The tests were performed in the dynamic and/or static modes and at different heights when applicable.

For the instrument classes of physically small instruments, three units of the same model and manufacturer were tested. For large instruments such as RPMs, Mobile systems, and SRPMs only one unit was tested. In the tables throughout the report that denote "yes/no" answers to the element in question, the response was denoted "yes" if at least two out of the three instruments (or two out of two instruments or one out of one instrument) passed the test. Conversely,"no," was denoted if the conditions are not met for the element in question.

For some instrument classes, data was shown to the operator on a display during the tests (e.g., a computer or instrument screen) and was also exported to an event file. The data displayed to the operator are reported in the following tables, unless otherwise noted. If discrepancies were observed, these differences are noted in the text.

For the environmental, mechanical and electromagnetic tests, when the instruments were exposed to each of the influence quantities (e.g., temperature, RF, vibration), the performance was verified by checking that the gamma exposure or ambient dose equivalent rate and neutron count rates readings were the same before (pre-test) and after (post-test) the test within a given range. If the instrument performed radionuclide identifications, the identification of the sources after being exposed to an influence quantity needed to be the same or better than the radionuclide identifications before the test. In the following tables, the gamma "response" of the instrument includes results from identifications (if applicable), except for the SPRDs due to the potential limitations in their identification capabilities. For these cases, identification results are considered separately. In addition, testers checked that no spurious indications, such as alarms, high ambient dose equivalent rate values, or instrument shut-down, were observed when exposed to the different influence quantities when no radioactive sources are present. For certain tests that required measurements in multiple orientations (e.g., three orthogonal axes in the magnetic field test), the instrument response was considered to be unaffected only if the response was unaffected in all orientations.

Throughout the report, the different sources used for testing are identified with general names, these names are listed in Table 1.

For purposes of this report, if the respective ANSI/IEEE and IEC requirement for a particular test differed, the more stringent requirement was chosen.

## 2.1 Test Results for Personal Radiation Detectors (PRDs)

Fourteen PRD models were tested (3 units per model), seven were equipped with neutron detectors. DNDO tested 9 models and JRC tested 5 models (see Table 2), 3 of the models tested by DNDO were the same as those tested by the JRC. A complete summary of the test results for the PRDs can be found in references [1] and [2]. These instruments were not intended to provide an accurate measurement of the ambient dose equivalent rate or exposure rate. Commercial Off The Shelf (COTS) PRDs can be divided into three broad categories.

- Unit-less display (without direct correlation to exposure rate or ambient dose equivalenet rate): These PRDs display a single digit that is related to intensity of the radiation field (larger numbers, larger

Table 1: List of names assigned to the different sources used for testing.

| Assigned Name | Sources |
|---|---|
| Special Nuclear Materials (SNM) | Highly-enriched uranium (HEU), weapons-grade plutonium (WGPu) |
| Naturally Occurring Radioactive Material (NORM) | Potassium-40, thorium-232, radium-226 |
| Medical sources | Gallium-67, technetium-99m, iodine-131, thallium-201, placed inside a 8 cm thick polymethyl methacrylate (PMMA, commonly known as acrylic or Plexiglas®) container to mimic in-vivo measurements |
| HEU-like source | Cobalt-57 |
| WGPu-like source | Barium-133 |
| Industrial sources | Cobalt-57, cobalt-60, barium-133, cesium-137, iridium-192. Americium-241 and depleted uranium (DU) are sometimes considered separately. |
| Low-energy gamma-ray source | Americium-241 |
| Medium-energy gamma-ray source | Cesium-137 |
| High-energy gamma-ray source | Cobalt-60 |
| Unmoderated neutron source | Californium-252 source shielded with steel and lead |
| Moderated neutron source | Californium-252 source placed inside a high density polyethylene (HDPE) or PMMA container (4 cm or 8 cm thick) |

fields). Most of these instruments display a single digit ranging from 1 to 9. These PRDs can be used for source localization.

- Unit-less display that is related to exposure or ambient dose equivalent rate: These PRDs display a single digit that is related to the intensity of the radiation field (larger numbers corresopnd to larger fields). Most of these instruments display a maximum value of (9). For each value displayed, the manufacturer normally provides the corresponding value (or range) of the exposure rate or ambient dose equivalent rate. These PRDs can be used for source localization and provide some information about the value of the radiation field.

- PRDs displaying multiple levels of information, including count rate and exposure or ambient dose equivalent rate: These instruments generally provide different alarms for security and for the safety of the operators. Both are monitored separately, and the threshold levels can be set accordingly. Some models can record the ambient dose equivalent rate to which the operator was exposed so that a total dose can be determined. These types of instruments can span a wide range of dose rates with some instruments reaching saturation in very high radiation fields.

Table 2: System information for PRDs. Instruments were tested by DNDO, unless denoted with * for those tested by JRC.

| Manufacturer/Model | Weight (g) | Size (cm) | Gamma Sensor | Gamma Dose Range ($\mu$Sv/h) | Neutron Sensor |
|---|---|---|---|---|---|
| Mirion-MGP/ PDS100GN* | 300 | 12.5×6.8×3.5 | CsI(Tl) | 0.01 - 100 | LiI(Eu) |
| Polimaster/PM1703GNA | 200 | 8.7×7.2×3.2 | CsI(Tl) | 0.01 - 99.99 | LiI(Eu) |
| Polimaster/PM1703GNA* | 200 | 8.7×7.2×3.2 | CsI(Tl) | 0.01 - 70 | LiI(Eu) |
| Polimaster/PM1703GNM | 230 | 9.8×7.5×3.5 | CsI(Tl), GM Tube | 0.01 - 9999 | LiI(Eu) |
| Polimaster/PM1703MO-1 | 250 | 9.8×7.5×3.2 | CsI(Tl), GM Tube | 0.01 - 9.99 | None |
| Polimaster/PM1703MO-1* | 250 | 9.8×7.5×3.2 | CsI(Tl), GM Tube | 0.01 - 9.99 | None |
| RAE/GammaRAE II R | 310 | 12.5×6.8×3.5 | CsI (Tl), Si PIN diode | 0.01 - 9.99 | None |
| RAE/NeutronRAE II 3020 | 240 | 12.5×6.8×3.5 | CsI (Tl) | 0.01 - 40 | LiI(Eu) |
| RAE/NeutronRAE II 3021 | 280 | 12.5×6.8×3.5 | CsI (Tl) | 0.01 - 200 | LiI(Eu) |
| Rotem/SentiRAD-01G† | 130 | 9.9×5.5×2.4 | CsI (Tl) | 0.25 - 20 | None |
| Southern Scientific/Nemo† | 110 | 11.5×8×2.5 | CsI (Tl) | 0.3 - 100 | None |
| Thermo Scientific/RadEye GN* | 160 | 9.7×6×3 | NaI(Tl) | 0.01 - 250 | $^{6}$Li doped |
| Thermo Scientific/RadEye PRD | 160 | 9.6×6.1×3.1 | NaI(Tl) | 0.01 - 250 | None |
| Thermo Scientific/RadEye PRD* | 160 | 9.6×6.1×3.1 | NaI(Tl) | 0.01 - 250 | None |
| † PRDs with unit-less display, provide conversion table to go from 0-9 display to ($\mu$Sv/h). | | | | | |

**General Description and Requirements**

A summary of the general PRD characteristics is shown in Table 3. Most PRDs had a back-lit LCD display that was visible in low and high light levels and could either display exposure or ambient dose equivalent rate. Two of the PRDs had an LED unit-less display, and a conversion table was provided to translate the displayed values to exposure or ambient dose equivalent rate. All were equipped with visual, audible, and vibrational alarms. Most PRDs produced event files, though the formats were not N42.42 compliant [34]. Most PRDs used non-rechargeable batteries that were easy to replace without the use of special tools. Reference point markings, indicating the location of the detector(s), were generally not well indicated; some PRDs had a marking on a single face. All PRDs could be configured through an external computer. For most PRDs, the alarm threshold was set when the instrument was powered on, based on the measurement of background radiation at the actual location. Only two PRDs were certified for use in explosive atmospheres.

Table 3: General characteristics of PRDs. An "X" is used if the system has the feature, and an "O" if it does not. "ND" indicates that there is no data available or the instrument was not tested. "NA" is used for "not applicable".

| | **PRD** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** | **K** | **L** | **M** | **N** |
| Visual and/or audible alarm | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Cannot disable all alarms simultaneously | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| User interface simple and intuitive | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Means to affix PRD to user | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Reference point marking for detector (front or back and a side) | O | O | O | O | O | O | O | O | O | O | O | X | O | O |
| Reference point marking described in manual | X | X | O | X | X | X | ND | ND | X | ND | ND | ND | X | O |
| Certified to operate in explosive atmospheres | X | X | O | O | O | O | O | O | O | O | O | O | O | O |
| Event files produced | O | X | X | X | X | X | ND | ND | X | ND | ND | ND | X | X |
| Data file in ANSI N42.42 format | NA | O | O | O | O | O | ND | ND | O | ND | ND | ND | O | O |
| Low-battery indication | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Use non-rechargeable batteries | X | X | X | X | X | X | X | X | X | X | X | X | O | X |
| Battery lifetime, under no alarm conditions: $\geq$ 16 h for rechargeable batteries, 100 h for non-rechargeable | O | X | X | X | X | X | ND | ND | X | ND | ND | ND | ND | O |
| Battery lifetime, under continuous alarm conditions: $\geq$ 30 minutes | X | X | X | X | X | X | ND | ND | X | ND | ND | ND | ND | X |

**Radiological Tests**

False Alarm Test

The false alarm rate of the PRDs were tested at two different background radiation levels: one at a low background radiation level that corresponds to a field normally encountered at sea level and the other at a high background radiation level that can be encountered at larger altitudes. Most PRDs displayed less than 1 alarm in 10 hours at both background radiation levels. Four displayed a larger number of false alarms when tested at the higher background radiation level. Two displayed a larger number of false alarms when tested at the lower background radiation level.

Table 4: False alarm test for PRDs. Total number of gamma and neutron alarms for each PRD unit tested at two different background radiation levels. The time duration of the test per unit is expressed in hours. "ND" indicates that there is no data available or the instrument was not tested. "NA" is used for "not applicable" when PRDs do not have the detection capabilities.

| PRD | Time (h) | Low level background | | | | | | High level background | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Gamma Alarms Unit | | | Neutron Alarms Unit | | | Gamma Alarms Unit | | | Neutron Alarms Unit | | |
| | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| A | 10 | 0 | 0 | 0 | NA | NA | NA | 0 | 0 | 0 | NA | NA | NA |
| B | 10 | 1† | 0 | 1† | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| C | 15* | ND | 1† | 0 | ND | 0 | 0 | ND | 0 | 0 | ND | 5 | 2 |
| D | 10 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| E | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| F | 10 | 1 | 0 | 0 | NA | NA | NA | 0 | 0 | 0 | NA | NA | NA |
| G | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| H | 10 | 0 | 0 | 0 | NA | NA | NA | 0 | 0 | 0 | NA | NA | NA |
| I | 10 | 0 | 0 | 0 | NA | NA | NA | 0 | 0 | 2 | NA | NA | NA |
| J | 10 | 3 | 4 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| K | 10 | 0 | 0 | 0 | NA | NA | NA | 0 | 0 | 0 | NA | NA | NA |
| L | 10 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 4 | 2 | 5 |
| M | 10 | 0 | ND | ND | NA | NA | NA | 0 | 0 | 0 | NA | NA | NA |
| N | 10 | 0 | 0 | 0 | NA | NA | NA | 3 | 0 | 0 | NA | NA | NA |

* Instrument-hours for each of the 2 units tested.
† Undetermined (not recorded as either gamma or neutron) alarms were assigned as gamma alarms.

Gamma Radiation Detection Capabilities

Overall, most of the PRDs detected gammas in less than 2 seconds for the three sources used in the test at two different background radiation levels (Table 5 combines the low and high background results), when the source popped in front of the PRDs in less than 0.5 seconds. Most did not alarm in less than 2 seconds when tested at the high background radiation level for the high-energy gamma-ray source. Two did not alarm for all the trials for two of the sources. The test at the low background radiation level was repeated with the sources moving by the PRDs at a speed of 0.5 m/s. Most PRDs detected all three sources, three of the PRDs were unable to consistently alarm for two of the sources, and the two other PRDs had problems detecting two of the sources (these results are not shown in the table because it is not a requirement in the standards).

For the accuracy test for the low-energy radionuclide, no PRD produced readings within the expected accuracy range for all intensities, although some were within expected accuracy at specific intensities. With the high-energy radionuclide, two PRDs were within the expected range at all intensities; the others were outside the range for at least one intensity case. With the medium-energy radionuclide, half of the PRDs were within the expected range at all intensities; the others were outside the range for at least one intensity case. In the aggregate, PRDs were more likely to under represent the radiation field at low intensities than at high intensities.

When exposed to a radiation field larger than the maximum value that can be measured by the PRDs, all PRDs displayed an over-range indication in less than 5 seconds, with the exception of one PRD that took approximately 8 seconds to display over-range. Most PRDs stopped alarming in less than 5 minutes after the high radiation field was removed. Only two PRDs took longer than 5 minutes to stop alarming.

When a medium-energy gamma source slowly approaches a PRD, at a speed of 0.1 m/s, it is important that the PRD alarms, so the radiation field produced by the slowly moving source is not considered part of the background radiation. When tested with a slowly moving source, all PRDs produced a gamma alarm before the source stopped in front of the units.

The personal radiation alarm was verified to function to ensure that users will not be exposed to a large radiation field without being notified by the PRD. Of the fourteen PRDs tested, six did not have a personal radiation alarm, three alarmed in less than 2 seconds, three alarmed in more than 2 seconds, and two increased the frequency of the alarm indication as they were tested in the search mode.

Summaries of the results of these tests are shown in Table 5.

Table 5: Gamma radiation tests for the PRDs. An "X" is used for"yes", an "O" is used for "no", "ND" indicates that there is no data available or the instrument was not tested and "NA" is used for "not applicable" when PRDs do not have the detection capabilities. Sources of differing energy refer to gamma-ray sources.

| | PRD | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** | **K** | **L** | **M** | **N** |
| **Time to Alarm (for low-, medium- and high-energy gamma sources)** | | | | | | | | | | | | | | |
| Alarmed in all trials: low-energy | O | X | O | X | X | X | ND | ND | X | ND | ND | ND | X | X |
| Time to alarm $\leq$ 2 seconds | O | O | O | X | X | X | X | X | X | X | X | X | X | X |
| Alarmed in all trials: medium-energy | X | X | X | X | X | X | ND | ND | X | ND | ND | ND | X | X |
| Time to alarm $\leq$ 2 seconds | X | X | O | X | X | X | X | X | X | X | X | X | X | X |
| Alarmed in all trials: high-energy | X | X | O | X | X | X | ND | ND | X | ND | ND | ND | X | X |
| Time to alarm $\leq$ 2 seconds | O | O | O | O | O | O | X | X | O | X | O | X | O | O |
| **Accuracy ($\pm$ 30 % from reference value at all dose rates)** | | | | | | | | | | | | | | |
| Accurate at low-energy | O | O | O | O | O | O | O | O | O | O | O | O | O | O |
| Accurate at medium-energy | O | O | O | X | X | X | O | X | X | X | X | O | O | O |
| Accurate at high-energy | O | O | O | O | O | O | O | O | X | X | O | O | O | O |
| **Personal Protection Alarm (100 $\mu$S/h medium-energy gamma source)** | | | | | | | | | | | | | | |
| Equipped with personal protection alarm | X | X | X | O | O | O | O | O | X | X | X | X | X | O |
| Alarm in all trials | X | X | X | NA | NA | NA | NA | NA | X | X | X | X | X | NA |
| Time to alarm $\leq$ 2 seconds | O | O | X | NA | NA | NA | NA | NA | X | O | X | X | O | NA |
| **Slowly Moving Source (medium-energy gamma source, 0.1 m/s speed)** | | | | | | | | | | | | | | |
| Alarm in all trials | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| **Over-Range (2 times maximum or 100 $\mu$Sv/h medium-energy gamma source)** | | | | | | | | | | | | | | |
| Equipped with over-range indication | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Alarm or over-range displayed | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Alarm remained until source removed | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Returned to normal operation within 5 minutes | O | X | X | X | X | O | X | X | X | X | X | X | X | X |

Neutron Radiation Detection Capabilities

For PRDs with neutron detectors, when the source was exposed in front of the PRDs in less than 0.5 seconds, the time to alarm to neutrons was larger than 2 seconds, and in some cases it was up to approximately 20 seconds. In many cases, the PRDs did not alarm in the presence of the neutron source.

When a neutron source is slowly approaching a PRD, it is important that the PRD alarms, so the radiation field produced by the slowly moving source is not considered part of the background radiation. When tested with a slowly moving neutron source, all produced a neutron alarm before the source stopped in front of the PRD, except for PRD El (1 of the 3 units for that model) that did not alarm for some of the trials.

Six of the PRDs with neutron detection capabilities were tested with a gamma-ray radiation field, similar in intensity to that produced by medical sources in patients, to verify if a neutron alarm is not triggered due to the presence of the gamma-ray radiation field alone, meeting the standards requirements. Two of the PRDs did not produce neutron alarms when exposed to the gamma-ray radiation field alone.

Summaries of the results of these tests are shown in Table 6.

Table 6: Neutron radiation tests for the PRDs. An "X" is used for"yes", an "O" is used for "no", "ND" indicates that there is no data available or the instrument was not tested and "NA" is used for "not applicable" when PRDs do not have the detection capabilities. Tested with unmoderated neutron sources.

| | **PRD** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **B** | **C** | **D** | **E** | **G** | **J** | **L** |
| **Time to Alarm Unmoderated Neutrons ($^{252}$Cf - 2 $\times 10^4$ neutron/s)** | | | | | | | |
| Alarmed in all trials | O | O | O | O | ND | ND | ND |
| Time to alarm $\leq$ 2 seconds | O | O | O | O | O | O | O |
| **Slowly Moving Unmoderated Neutron Source ($^{252}$Cf - 2 $\times 10^4$ neutron/s, 0.1 m/s speed)** | | | | | | | |
| Alarmed in all trials | X | X | X | O | ND | ND | ND |
| **Neutron Indication in the Presence of Photons (gamma high-energy source at 100 $\mu$Sv/h)** | | | | | | | |
| No neutron response with gamma source only | O | X | O | O | X | ND | NA* |
| * The PRD went into danger condition so it was not possible to discriminate the neutron alarms. | | | | | | | |

## Environmental, Electromagnetic, and Mechanical Tests

Summaries of the results of these tests are shown in Tables 7, 8, and 9. These tests were not performed for PRDs tested at the JRC. In few cases, the temperature test was performed for a larger range of values because of the manufacturer's claims. Most PRDs had problems operating at +50°C. When the PRDs were moved from room temperature to +50°C, most PRDs worked correctly for the first 15 minutes, but their performance degraded over time as they were exposed to a high temperature for a long period of time. This is important to consider if users wearing PRDs move from an air-conditioned location to a location with temperature of +50 °C. The start-up time of most PRDs did not change when they were started at a low temperature, though in some cases the start-up took longer. Most PRDs showed no dust penetration, and the presence of dust did not affect the PRDs' response. Most PRDs were not water sealed, as evidenced by water penetrations during the test, but in several cases the PRDs continued to function as they dried. One PRD was not susceptible to radio frequency interferences. For those that displayed susceptibilities, they occured at different frequencies. PRDs did not produce radiated emissions that could interfere with the operations on neighboring devices. In general, PRDs were not susceptible to DC magnetic fields. One did not alarm during the vibration test. Several were not damaged by the drop test. Most were not susceptible to mechanical impacts.

Table 7: Environmental tests for the PRDs. An "X" is used for "yes", an "O" is used for "no", "N" is used for "none" if the instrument never worked correctly, "ND" indicates that there is no data available or the instrument was not tested and "NA" is used for "not applicable" when PRDs do not have neutron detection capabilities.

| | PRD | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **A*** | **B** | **C** | **D** | **E** | **F** | **I** | **M** | **N** |
| **Temperature Test (-20 °C to +50 °C)** | | | | | | | | | |
| Gamma response unaffected | O | O | O | O | O | O | X | O | O |
| Neutron response unaffected | O | O | O | O | X | O | X | O | O |
| Operational temperature range for gammas (°C) | -20 to +30 | -20 to +40 | -20 to +30 | -20 to +40 | -20 to +30 | -30 to +30 | -20 to +50 | -20 to +50 | +22 to +50 |
| Operational temperature range for neutrons (°C) | NA | N | N | +10 to +50 | -30 to +50 | NA | NA | NA | NA |
| **Humidity Test (40 % to 93 % RH at 35 °C)** | | | | | | | | | |
| Gamma response unaffected | X | X | X | X | O | X | X | ND | X |
| Neutron response unaffected | NA | O | O | X | X | NA | NA | ND | NA |
| **Temperature Shock Test (recover in 15-30 min, 20 °C to/from +50 °C, 20 °C to/from -20 °C)** | | | | | | | | | |
| Gamma response unaffected | X | O | O | X | O | X | X | ND | X |
| Neutron response unaffected | NA | O | O | X | X | NA | NA | ND | NA |
| **Cold Temperature Startup Test (start at -20 °C)** | | | | | | | | | |
| Gamma response unaffected | X | X | X | X | X | X | X | ND | X |
| Neutron response unaffected | NA | O | X | X | X | NA | NA | ND | NA |
| **Dust Test (IEC 60529 IP53 [35]** | | | | | | | | | |
| Instrument free of dust ingress | X | X | X | X | X | X | X | ND | O |
| Gamma response unaffected | X | X | X | X | X | X | X | ND | X |
| Neutron response unaffected | NA | O | O | X | X | NA | NA | ND | NA |
| **Moisture Test (IEC 60529 IP53 [35])** | | | | | | | | | |
| Instrument free of water ingress | O | O | O | O | O | O | O | ND | X |
| Gamma response unaffected | X | X | O | X | O | X | X | ND | O |
| Neutron response unaffected | NA | O | O | X | O | NA | NA | ND | NA |

* Temperature test was performed between -20 °C and +30 °C.

Table 8: Electromagnetic tests for the PRDs. An “X” is used for “yes”, an “O” is used for “no”, “N” for “none” worked correctly for all frequencies, “BR” is used for “broad range” when the instrument response is affected for a large number of frequencies, “ND” indicates that there is no data available or the instrument was not tested’ and “NA” is used for “not applicable” when PRDs do not have neutron detection capabilities.

| | PRD | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **I** | **M** | **N** |
| **Electrostatic Discharge Test (up to ±6 kV conductive surfaces and coupling planes)** | | | | | | | | | |
| Gamma response unaffected | X | X | X | X | O | O | X | ND | X |
| Neutron response unaffected | NA | O | O | O | O | NA | NA | NA | NA |
| **Radio Frequency (80 MHz to 2.5 GHz at 50 V/m)** | | | | | | | | | |
| Gamma response unaffected | O | O | O | O | O | O | X | O | O |
| Neutron response unaffected | NA | O | O | O | O | NA | NA | NA | NA |
| Frequencies with susceptibilities (MHz) | BR | BR | BR | BR | BR | 1105 to 1160 | N | 925 to 1104 | BR |
| **Radiated Emissions (from 30 to above 960 MHz at 100 to 500 $\mu$V/m)** | | | | | | | | | |
| Emissions lower than maximum allowed | X | X | X | X | X | X | X | X | X |
| **DC Magnetic Field Test (10 G; 3 orthogonal axes)** | | | | | | | | | |
| Gamma response unaffected | X | X | X | X | X | X | X | X | X |
| Neutron response unaffected | NA | O | O | X | X | NA | NA | NA | NA |
| 10 G = 1 mT | | | | | | | | | |

Table 9: Mechanical tests for the PRDs. An “X” is used for “yes”, an “O” is used for “no”, “ND” indicates that there is no data available or the instrument was not tested and “NA” is used for “not applicable” when PRDs do not have neutron detection capabilities.

| | PRD | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **I** | **M** | **N** |
| **Drop Test (from 1.5 m on a concrete floor)** | | | | | | | | | |
| Instrument free of damage | X | X | X | O | O | X* | O | X | O |
| Gamma response unaffected | X | X | X | O | O | X | X | X | O |
| Neutron response unaffected | NA | O | O | O | O | NA | NA | NA | NA |
| **Vibration Test (random vibration, 0.01 $g^2$/Hz, 5 and 500 Hz endpoints)** | | | | | | | | | |
| Instrument free of damage | X | X | X | X | X | X | X | ND | O |
| Instrument did not alarm due to vibration | O | O | O | O | O | O | X | ND | O |
| Gamma response unaffected | X | X | X | X | O | X | X | ND | X |
| Neutron response unaffected | NA | O | O | X | X | NA | NA | NA | NA |
| **Impact Test (0.2 J impacts)** | | | | | | | | | |
| Instrument free of damage | X | X | X* | X | X | X* | O | X | X |
| Instrument did not alarm due to impact | X | X | X | X | X | X | X | X | X |
| Gamma response unaffected | X | X | X | X | X | X | X | X | X |
| Neutron response unaffected | NA | O | O | X | X | NA | NA | NA | NA |
| * 1 out of 3 units damaged. | | | | | | | | | |

## 2.2 Test Results for Spectroscopic Personal Radiation Detectors (SPRDs)

A total of six models of Spectroscopic Personal Radiation Detectors (SPRDs) were tested (see Table 10). Two models (three units each) were tested only by DNDO, one model (two units) was tested only at JRC, and three models (three units each) were tested by both DNDO and JRC. A complete summary of the test results for the SPRDs can be found in references [3] and [4].

Table 10: System information for SPRDs. Instruments were tested by DNDO, unless denoted with * for those tested by JRC.

| Manufacturer/Model | Mass (g) | Size (cm) | Gamma Sensor | Gamma Dose Range ($\mu$Sv/h) | Neutron Sensor |
|---|---|---|---|---|---|
| ATOMTEX/AT1321* | 700 | 14.5×10.0×5.0 | NaI(Tl) | 0.03 – 300 | None |
| FLIR/nanoRaider | 370 | 12.5×7.1×3.5 | CdZnTe and GM tube | <0.1 – 10000 | $^3$He |
| Mirion/PDS100GN/ID | 370 | 12.7×7.8×4.4 | CsI(Tl) | 0 – 100 | LiI(Eu) |
| Mirion/PDS100GN/ID* | 370 | 12.7×7.8×4.4 | CsI(Tl) | 0 – 100 | LiI(Eu) |
| Polimaster/PM1704GN | 350 | 12.9×5.8×4.5 | CsI(Tl) | 0.01 – 130 | LiI |
| Polimaster/PM1704GN* | 350 | 12.9×5.8×4.5 | CsI(Tl) | 0.01 – 130 | LiI |
| Polimaster/PM1704M | 330 | 12.9×5.8×4.5 | CsI(Tl) and GM tube | 0.01 – $1.3\times10^7$ | None |
| Polimaster/PM1704M* | 330 | 12.9×5.8×4.5 | CsI(Tl) and GM tube | 0.01 – $1.3\times10^7$ | None |
| RadComm/Mspec | 220 | 12.1×6.8×3.7 | CsI(Na) | 0.01 – 130 | $^3$He |

### General Description and Requirements

A summary of general description and requirements for SPRDs is shown in Table 11. In addition to identifying radionuclides, each instrument displayed at least the relative intensity of the radiation field and provided an audible and/or vibrating alarm to indicate an increase in the radiation level that was greater than the alarm set point. All instruments came with clips or lanyards to securely fix the instrument to the user and have a simple user interface for non-expert users. SPRDs are not primarily intended to provide a measurement of dose-equivalent rate. However, their indication can provide an approximate value of ambient dose equivalent rate that should be reasonably accurate.

For the SPRDs where data from both the display visible to the operator and the event files were recorded (A,B, E, and G), the results were generally consistent, though some inconsistencies did arise. For SPRD E, the list of radionuclides identified was not always the same between the display and the file, and the number of identifications could be quite different. SPRDs B and G often found a large number of “secondary“ identifications in the saved file that did not appear on the display.

Table 11: General characteristics of SPRDs. An “X” indicates the system has a feature, and an “O” indicates that it does not. “ND” indicates that there is no data available or the instrument was not tested.

| | **SPRD** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Feature | A | B | C | D | E | F | G | H | I |
| Battery lifetime exceeds 30 minutes in alarmed state | ND | ND | X | X | ND | X | ND | X | X |
| Battery lifetime exceeds 16 hours in non-alarmed state | ND | ND | O | O | O | O | ND | X | X |
| Batteries are rechargeable | X | O | X | X | O | X | O | X | X |
| Possible to transfer data to computer | X | X | X | X | X | X | X | X | X |
| Data file in ANSI N42.42 format | O | O | O | X | O | X | O | ND | X |
| No more than one false alarm per 10-hour shift | X | X | O | X | X | O | X | O | X |
| Instrument provides search mode | X | X | O | X | X | X | X | X | X |
| Instrument reliably indicates over-range condition | X | X | O | X | ND | X | ND | X | X |
| Operable with gloves | ND | ND | X | X | ND | X | ND | X | X |
| Battery status indicated | X | X | X | X | X | X | X | X | X |
| Display readable in high lighting conditions | O | O | X | X | X | X | O | X | X |
| Display readable in low lighting conditions | X | X | X | X | X | X | X | X | X |
| Simple to use for non-experts | X | X | X | X | X | X | X | X | X |

### Radiological Tests

Radiological tests were performed to test instrument detection and identification response to both gamma and neutron radiation sources. The following outlines the highlights from these tests.

False Alarm Test

False alarm tests were performed by putting instruments in search mode and setting the alarm signal threshold at the threshold level as recommended by the manufacturer. Multiple instruments were put in normal background ambient dose equivalent rate conditions and monitored for at least 30 instrument-hours (e.g., 3 instruments for 10 hours). A summary of the results is shown in Table 12. Most of the instruments performed well, with the exception of SPRD C, which had a high false alarm rate for gammas, and SPRDs F and H, in which each of the three respective units failed for neutron false alarms.

Gamma Radiation Detection Capabilities

Results are shown in Table 13. For the Time to Alarm test, all instruments were able to detect sources within 3 seconds for all conditions tested, except SPRD I. For this SPRD, the data indicated that the repetition rate of the test was too high (i.e., the instrument was attempting to adjust backgrounds over a time scale longer than the time between exposures).

The accuracy of the gamma dose-equivalent readout was tested by exposing the instruments to a variety of sources and dose-equivalent rates. The low-energy gamma source and sources with high intensities were challenging for many instruments. Except for high-intensity low-energy gamma fields, most of the instruments were fairly close to being within the required range of the correct rate.

The personal radiation alarm is intended to alert the wearer of an instrument that they have entered a rel-

Table 12: False alarm test for SPRDs. Number of false alarms recorded during the specified number of hours of observation. "ND" indicates that the instrument was not tested under those conditions. "NA" is used for "not applicable" when SPRDs do not have neutron detection capabilities. "g" denotes gamma false alarms, "n" denotes neutron false alarms.

| | | Low Background | | | | | | High Background | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Unit 1 | | Unit 2 | | Unit 3 | | Unit 1 | | Unit 2 | | Unit 3 | |
| **SPRD** | **Duration (h)** | **g** | **n** | **g** | **n** | **g** | **n** | **g** | **n** | **g** | **n** | **g** | **n** |
| A | 10 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 2 | 1 | 0 |
| B | 10 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| C | 10 | 12 | 0 | 15 | 0 | 55 | 0 | ND | ND | ND | ND | ND | ND |
| D | 10 | 0 | NA | 1 | NA | 0 | NA | NA | NA | NA | NA | NA | NA |
| E | 15 | 0 | NA | 0 | NA | 0 | NA | 1 | NA | 0 | NA | 0 | NA |
| F | 10 | 1 | 3 | 1 | 3 | 0 | 5 | ND | ND | ND | ND | ND | ND |
| G | 10 | 0 | NA | 0 | NA | 0 | NA | 0 | NA | 0 | NA | 0 | NA |
| H | 10 | 0 | 6 | 0 | 9 | 0 | 2 | ND | ND | ND | ND | ND | ND |
| I | 10 | 0 | 0 | 0 | 0 | 0 | 1 | ND | ND | ND | ND | ND | ND |

atively high-intensity radiation field. All instruments (for which data was reported) indicated the personal protection alarm in less than 5 seconds when exposed to such a field. Over-range indications alert users to potentially high radiation fields. Only instrument C failed to reliably indicate that it was over range, but it was tested at such high levels (more than 100x its specified range, when the specification states the maximum will be at 10x) that this is not surprising. Data was not provided for either instrument E or instrument G.

Table 13: Gamma radiation tests for the SPRDs. An "X" is used for "yes", and an "O" is used for "no". Sources of differing energy refer to gamma-ray sources. "ND" indicates that there is no data available or the instrument was not tested.

| | SPRD | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** |
| **Time to Alarm: Gamma Sources** | | | | | | | | | |
| Alarm in all trials: low-energy gamma | ND* | ND* | X | X | ND* | X | ND* | X | X |
| Time to alarm $\leq$ 3 seconds | X | X | X | X | X | X | X | X | X |
| Alarm in all trials: medium-energy gamma | ND* | ND* | X | X | ND* | X | ND* | X | X |
| Time to alarm $\leq$ 3 seconds | X | X | X | X | X | X | X | X | X |
| Alarm in all trials: high-energy gamma | ND* | ND* | X | X | ND* | X | ND* | X | X |
| Time to alarm $\leq$ 3 seconds | X | X | X | X | X | X | X | X | O |
| **Accuracy** | | | | | | | | | |
| Accurate to $\pm$ 30 %: low-energy gamma | O | O | O | O | O | O | O | O | O |
| Accurate to $\pm$ 30 %: medium-energy gamma | O | X | X | X | X | X | X | X | X |
| Accurate to $\pm$ 30 %: high-energy gamma | O | X | X | X | X | O | X | X | X |
| **Personal Protection Alarm** | | | | | | | | | |
| Alarm in all trials | ND* | ND* | X | X | ND* | X | ND* | X | X |
| Time to alarm $\leq$ 5 seconds | X | ND | X | X | X | X | X | X | X |
| **Over-Range** | | | | | | | | | |
| Equipped with over-range indication | X | X | X | X | X | X | X | X | X |
| Alarm or over-range displayed | X | X | O | X | ND | X | ND | X | X |
| Remain in alarm until source removed | ND | ND | ND | X | ND | X | ND | X | X |
| Return to normal operation within 5 minutes | X | X | X | X | ND | X | ND | X | X |
| *The detailed reports for these instruments did not specify the fraction of trials for which there was an alarm, but did, in general, specify the time to alarm. | | | | | | | | | |

Neutron Radiation Detection Capabilities

Results are shown in Table 14. All instruments with neutron alarm capabilities, except C and H, responded reliably within 5 seconds when exposed to a neutron source. None of the SPRDs had dose-equivalent readout for neutrons, so the accuracy test could not be performed. SPRDs D, E, and G did not have neutron capabilities.

Table 14: Neutron radiation tests for the SPRDs. An "X" is used for "yes", and an "O" is used for "no". "ND" indicates that there is no data available or the instrument was not tested. "NA" is used for "not applicable" when SPRDs do not have neutron detection capabilities.

| | SPRD | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** |
| **Time to Alarm** | | | | | | | | | |
| Alarm in all trials | ND | ND | O | NA | NA | X | NA | X | X |
| Time to alarm $\leq$ 5 seconds | X | X | O | NA | NA | X | NA | O | X |

Radionuclide Identification

Most systems performed well for identification of single radionuclides, although most had moderate difficulty with medical radionuclides. SPRD C was anomalous in that it identified the medical radionuclides with a high probability, but performed relatively poorly for the rest of the sources. One of the units tested for SPRD D appeared to be malfunctioning, as it failed to identify any radionuclides (the other units performed well). SPRDs H and I did not identify the SNM sources as often as other SPRDs. Some of the instruments (B, D, F, and G) identified a large number of other radionuclides (that were not present) in addition to the correct radionuclide. SPRDs E, F, G, and I performed better than other SPRDs at their respective test facilities for simultaneously identifying multiple radionuclides.

For the Masking Tests with medical-industrial source pairs, the instruments generally correctly identified both radionuclides. Results were more mixed when masking an SNM radionuclide. SPRDs E and C could not see any SNM reliably through the masking source. SPRD I could not identify any plutonium sources reliably through the masking source. SPRD B and G were stellar at identifying the masked industrial/medical sources, had some success with HEU, and displayed difficulty with plutonium. SPRDs D, H, and F could identify HEU and RGPu but not WGPu. In contrast, SPRD A often identified the masked SNM sources but could not separate the masked industrial-medical source pairs.

When presented with a radionuclide that was not in their library of known materials, each SPRD correctly reported that it was not identifiable or was unknown, though some instruments reported (with lower confidence) radionuclides that *were* in their libraries.

**Environmental, Electromagnetic, and Mechanical Tests**

Summaries of the test results are shown in Tables 15, 16, and 17. Because a low-intensity field was used for neutrons, statistical fluctuations were high for many SPRDs, and it could not be readily determined if the reading had shifted because of the test, or simply because of a statistical fluctuation in the reading. This was true to a lesser extent for some instruments that did not always identify the medium-energy gamma radionuclide correctly.

Of the instruments that were tested (SPRD C, D, F, H, I), the gamma response and identifications were stable across a wide range of temperatures and humidity values for most SPRDs; neutron response was more mixed. SPRD H met the requirements for nearly all environmental tests. Results were similar for the electromagnetic interference tests, with SPRD I meeting all of the requirements. Most of the instruments did well in the mechanical tests, except for the drop test where only SPRD I was undamaged. SPRDs C and D were damaged in the impact test.

Table 15: Environmental tests for the SPRDs. An "X" is used for "yes", and an "O" is used for "no". "ND" indicates that there is no data available or the instrument was not tested. Instruments that do not appear in this table were not tested for environmental sensitivity. For many instruments, high statistical variability in neutron rates showed up as environmental sensitivity.

| | SPRD | | | | |
|---|---|---|---|---|---|
| | C | D | F | H | I |
| **Temperature Test (–20 °C to +50 °C)** | | | | | |
| Gamma response unaffected | O | O† | X | X | X |
| Neutron response unaffected | O | ND | O | X | O |
| Radionuclide ID unaffected | X | O** | O* | X | X |
| Gamma operational temperature range (°C) | +20 to +50 | -20 to +50 $^{\alpha}$ | -20 to +50 | -20 to +50 | -20 to +50 |
| Neutron operational temperature range (°C) | -20 to +40 | ND | 0 to +50 | -20 to +40 | +10 to +50 |
| **Humidity Test (40 % to 93 % RH at 35 °C)** | | | | | |
| Gamma response unaffected | X | X | X | X | X |
| Neutron response unaffected | O | ND | X | X | O |
| Radionuclide ID unaffected | X | X | X | X | X |
| **Temperature Shock Test (recover in 15-30 min, 20 °C to/from +50 °C, 20 °C to/from –20 °C)** | | | | | |
| Gamma response unaffected | X | X | X†† | X | X |
| Neutron response unaffected | O | ND | O | O | O |
| Radionuclide ID unaffected | O | X | O | X | O |
| **Cold Temperature Startup Test (start at –20 °C)** | | | | | |
| Gamma response unaffected | X | X | X | X | X |
| Neutron response unaffected | O | ND | O | X | X |
| Radionuclide ID unaffected | O | X | O | X | X |
| **Warm Temperature Startup Test (start at 50 °C)** | | | | | |
| Gamma response unaffected | X | X | X | X | X |
| Neutron response unaffected | O | ND | O | X | O |
| Radionuclide ID unaffected | X | X | O | X | X |
| **Dust Test (IEC 60529 IP53 [35])** | | | | | |
| Instrument free of dust ingress | X | X | X | X | X |
| Gamma response unaffected | X | X | X | X | X |
| Neutron response unaffected | X | ND | X | X | X |
| Radionuclide ID unaffected | O | X | X | X | X |
| **Moisture Test (IEC 60529 IP53 [35])** | | | | | |
| Instrument free of water ingress | O | O | O | X | X |
| Gamma response unaffected | X | X | X | X | X |
| Neutron response unaffected | O | ND | O | X | X |
| Radionuclide ID unaffected | X | X | X | X | X |

* Radionuclide ID affected only at –20 °C

** Radionuclide ID affected only at –20 °C, 50 °C

$^{\alpha}$ All three units did not met specifications only at 0 °C

† Gamma response affected only at 0 °C

†† One unit (of three) froze during testing

Table 16: Electromagnetic tests for the SPRDs. An "X" is used for "yes", and an "O" is used for "no". "ND" indicates that there is no data available or the instrument was not tested. Instruments that do not appear in this table were not tested for electromagnetic sensitivity. For many instruments, high statistical variability in neutron rates showed up as electromagnetic sensitivity.

| | SPRD | | | | |
|---|---|---|---|---|---|
| | C | D | F | H | I |
| **Electrostatic Discharge Test (up to ±6 kV)** | | | | | |
| Gamma response unaffected | X | O | X | X | X |
| Neutron response unaffected | O | ND | O | X | X |
| Radionuclide ID unaffected | X | X | X | X | X |
| **Radio Frequency (80 MHz to 1 GHz, 1.4 GHz to 2.5 GHz at 20 V/m)** | | | | | |
| Gamma response unaffected | X | X | X | X | X |
| Neutron response unaffected | O | ND | O | O | X |
| Radionuclide ID unaffected | X | X | X | X | X |
| Frequencies with susceptibilities | BR 1-2.5 GHz | N | 1.28 GHz | BR 1-2.5 GHz | N |
| **Radiated Emissions (30 to $>$ 960 MHz at 100 to 500 $\mu$V/m)** | | | | | |
| Emissions lower than maximum allowed | X | X | X | X | X |
| **DC Magnetic Field Test (10 G; 3 orthogonal axes)** | | | | | |
| Gamma response unaffected | X | X | X | X | X |
| Neutron response unaffected | O | ND | X | X | X |
| **AC Magnetic Field Test (30 A/m 50 Hz; 3 orthogonal axes)** | | | | | |
| Gamma response unaffected | X | X | X | X | X |
| Neutron response unaffected | O | ND | X | X | X |

Table 17: Mechanical tests for the SPRDs. An “X” is used for “yes”, and an “O” is used for “no”. “ND” indicates that there is no data available or the instrument was not tested. SPRDs that do not appear in this table were not tested for mechanical sensitivity. For many SPRDs, high statistical variability in neutron rates showed up as mechanical sensitivity.

| | **SPRD** | | | | |
|---|---|---|---|---|---|
| | C | D | F | H | I |
| **Vibration Test (random vibration, 0.01 $g^2$, 5 and 500 Hz endpoints)** | | | | | |
| Instrument free of damage | O | X | X | X | X |
| Gamma response unaffected | X | X | X | X | X |
| Neutron response unaffected | O | ND | X* | X | O |
| Radionuclide ID unaffected | X | X | X | X | X |
| **Mechanical Shock Test (50 g peak acceleration, half sine-wave over 11 ms)** | | | | | |
| Instrument free of damage | X | X | X | X | X |
| Instrument did not alarm due to shock | X | X | O | X | O |
| Gamma response unaffected | X | X | X | X | X |
| Neutron response unaffected | O | ND | O | X | O |
| Radionuclide ID unaffected | ND | X | X | X | X |
| **Impact Test (0.2 J impacts)** | | | | | |
| Instrument free of damage | O | O | X | X | X |
| Gamma response unaffected | X | X | X | X | X |
| Neutron response unaffected | O | ND | X | X | O |
| Radionuclide ID unaffected | X | X | X | X | X |
| **Drop Test (from 1 m on a concrete floor in shipping case)** | | | | | |
| Instrument free of damage | O | O | O | O | X |
| Gamma response unaffected | ND | ND | ND | ND | X |
| Neutron response unaffected | ND | ND | ND | ND | X |
| Radionuclide ID unaffected | ND | ND | ND | ND | ND |
| * Modestly affected in Y-axis only | | | | | |

## 2.3 Test Results for Gamma Search Detectors (GSDs)

Four GSDs were tested (see Table 18), two each by DNDO and the JRC (one model was tested by both facilities with different alarm threshold settings). A complete summary of the test results for the GSDs can be found in references [5] and [6].

Table 18: System information for GSDs. Instruments were tested by DNDO, unless denoted with * for those tested by JRC. The note concerning threshold for the Thermo Scientific units refers to the amount the radiation signal needs to be above background in order for the instrument to alarm.

| Manufacturer/Model | Weight (kg) | Gamma Sensor | Dose Range ($\mu$Sv/h) | Neutron Sensor |
|---|---|---|---|---|
| Mirion HDS100* | 1.5 | CsI(Tl) | 0.01 − 100† | LiI(Eu) |
| RadComm Systems RC2 | 2.4 | PVT | 0.03 − 3 | None |
| Thermo Scientific RadEye NBR (6$\sigma$ threshold) | 3.0 | Scintillator | 0.01 − 100 | None |
| Thermo Scientific RadEye NBR* (4$\sigma$ threshold) | 3.0 | Scintillator | 0.01 − 100 | None |
| †10 Sv/h maximum for the extended range version. | | | | |

### General Description and Requirements

A summary of the general information for GSDs is shown in Table 19. All instruments produced visual and/or audible alarms with a simple user interface. Most also provided a silent alarm and event files, though the formats were not ANSI/IEEE N42.42 [34] compliant. The instruments for which battery life could be assessed performed very well. Reference point markings were generally not well indicated.

Table 19: General characteristics of GSDs. An "X" is used if the system has the feature, and an "O" if it does not. "ND" indicates that there is no data available or the instrument was not tested, and "NA" is "not applicable".

| | GSD | | | |
|---|---|---|---|---|
| | A | B | C | D |
| Visual and/or audible alarm | X | X | X | X |
| Silent alarm | O | X | X | X |
| User interface simple and intuitive | X | X | X | X |
| Warm up time: $\leq$ 2 minutes | X | X | X | X |
| Event files produced | O | X | X | X |
| If yes, N42.42 format | NA | O | O | O |
| Ability to run on AC or DC power | O | O | ND | ND |
| Certified to operate in explosive atmospheres | O | O | O | O |
| Reference point marking for detector center (front/back) | O | X | O | O |
| Reference point marking for detector center (side) | O | X | O | X |
| Low-battery indication | X | X | ND | ND |
| Battery lifetime, under no alarm conditions: $\geq$ 16 hours | X | X | ND | ND |
| Battery lifetime, under continuous alarm conditions: $\geq$ 30 minutes | X | X | ND | ND |

### Radiological Tests

Radiological tests were performed to test instrument alarm and exposure rate (or ambient dose equivalent rate) response to gamma radiation sources. The following outlines the highlights from these tests.

False Alarm Test

The false alarm rate was determined by observing the instruments for 20 hours and 10 minutes (DNDO) or 10 hours (JRC). Results are shown in Table 20. False alarms were generally not triggered often. For GSDs C and D, the number of false alarms by each of the three units (per instrument model) was aggregated to the total number of false alarms in 30 instrument-hours [23]. For the observed rate of 9 false alarms in 30 instrument-hours for GSD D, the 95 % upper confidence bound on the false alarm rate would be 0.52 alarms per hour (assuming a Poisson distribution), which is still below the requirement of a rate no more than 1 false alarm per hour.

Table 20: False alarm test for the GSDs

| GSD | Duration (h:min) per instrument | Unit | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| A | 20:10 | 0 | 0 | 1 |
| B | 20:10 | 0 | 2 | 2 |
| C | 30:00* | 0 | | |
| D | 30:00* | 9 | | |
| * Instrument-hours: 3 units times 10 hours. | | | | |

Gamma Radiation Detection Capabilities

Results are shown in Table 21. In general, all instruments performed well when the alarm response time was tested with a variety of sources. GSD D always alarmed in less than 5 seconds for each source. GSD C also alarmed as quickly, though encountered difficulty with a high-energy source. This source proved even more troublesome for GSDs A and B, where response time was often more than double the required time, if alarms were triggered at all. For the low-energy source, although two units of GSD A consistently alarmed in less than 3 seconds, the time to alarm for the third unit was greater than this limit in 70 % of the trials.

The accuracy of the ambient dose equivalent rate was measured for a range of rates and sources. Only rates below the respective over-range conditions were considered. GSD B was very accurate across each tested radionuclide at all rates. GSD A was only slightly out of range for the medium- and high-energy gamma sources for a few rates. GSD C displayed a wide variety of inaccurate dose rates.

GSDs B, C, and D were instrumented with personal protection alarms (for safety purposes), to reject natural background variation, and have the ability to discriminate the type or category of radiation (i.e., medical or NORM sources from other sources). To test the personal protection alarm, the instruments were exposed to a source that yields a count rate or ambient dose equivalent rate greater than the personal protection alarm threshold. Although each GSD alarmed in all trials, only GSD B did so with an average time to alarm that was less than two seconds. GSDs B and D did not have the ability to distinguish medical sources, though generally performed well in categorizing other tested sources. GSD C correctly categorized all tested sources in nearly every trial.

Natural background rejection is important to avoid alarms simply because of sharp, natural changes in background. When exposed to an artificial change in background using NORM sources, GSD C displayed slightly fewer alarms with the background rejection feature enabled (a positive outcome), but GSD D showed no change, alarming in all trials to the background change. GSD B performed very well, with no alarms due to the background change with or without the feature enabled.

There was no data to indicate if GSDs were equipped with specific over-range indications. Results in Table 21 allow for either an alarm or indication. GSD C was not tested for safety reasons because its over-range condition is achieved at a very high ambient dose equivalent rate. All other GSDs accurately alarmed and returned to normal operation in less than five minutes after the source was removed. GSDs B and D also remained in the alarm state for the entire duration of exposure to the source. GSD A stopped indicating the indication one second after exposure and displayed a lower, incorrect dose equivalent rate for the remainder of the exposure, which can be unsafe for users.

**Environmental, Electromagnetic, and Mechanical Tests**

Summaries of the results of these tests are shown in Tables 22, 23, and 24. In general, the two tested models performed very well and displayed the ability to operate in a wide variety of temperatures and humidity values, as well as dusty and moist environments. The readings of each model were within the allowed range of the pre-test value for all mechanical tests, and each sustained electrostatic discharges up to 6 $\pm$kV without any damage. Radiated emissions of each were well below the maximum level allowed. RF susceptibilities were observed on GSD A model for a narrow frequency range (84 to 86 MHz) on only one unit. Generally, both GSDs performed better in an AC magnetic field than a DC magnetic field. During the humidity test, one unit of GSD B was only slightly out of range for 2 hours (in the middle of a 16 hour soak at 93 % humidity), and one unit stopped working when humidity reached 93 %. Both GSDs met all mechanical test requirements.

Table 21: Radiation tests for the GSDs. An "X" is used for "yes", and an "O" is used for "no". Sources of differing energy refer to gamma-ray sources. "ND" indicates that there is no data available or the instrument was not tested. "NA" indicates "not applicable".

| | GSD | | | |
|---|---|---|---|---|
| | **A** | **B** | **C** | **D** |
| **Time to Alarm (for low-, medium-, and high-energy gamma sources)** | | | | |
| Alarmed in all trials: low-energy | X | X | X | X |
| Time to alarm $\leq$ 3 seconds in all trials | X | X | X | X |
| Alarmed in all trials: medium-energy | X | O | X | X |
| Time to alarm $\leq$ 3 seconds in all trials | X | O | X | X |
| Alarmed in all trials: high-energy | O | O | O | X |
| Time to alarm $\leq$ 3 seconds in all trials | O | O | O | X |
| **Accuracy ($\pm$ 30 % from reference value at all dose rates)** | | | | |
| Accurate at low-energy | X | X | O | O |
| Accurate at medium-energy | O | X | O | X |
| Accurate at high-energy | O | X | O | X |
| **Personal Protection Alarm (30 % above personal protection threshold)** | | | | |
| Equipped with personal protection alarm | O | X | X | X |
| Alarmed in all trials | NA | X | X | X |
| Time to alarm $\leq$ 2 seconds | NA | X | O | O |
| **Natural Background Rejection (NBR; 0.1 $\mu$Sv/h NORM source)** | | | | |
| Number of alarms due to change in background reduced with NBR feature enabled | O | X† | X | NA |
| **Over-Range (10 mSv/h medium-energy gamma source)** | | | | |
| Equipped with over-range indication | ND | ND | ND | ND |
| Alarm in over-range conditions | X | X | ND | X |
| Alarm remained until source removed | O | X | ND | X |
| Returned to normal operation within 5 minutes | X | X | ND | X |
| **Source Categorization (multiple gamma sources from each category)** | | | | |
| Accurate categorization in all trials: medical sources | NA | O* | X | O* |
| Accurate categorization in all trials: NORM sources | NA | O | X | O |

† Zero alarms with and without the NBR feature enabled.
* Instrument does not have this capability.

Table 22: Environmental tests for the GSDs. An “X” is used for ”yes”, and an “O” is used for ”no”.

| | GSD | |
|---|---|---|
| | **A** | **B** |
| **Temperature Test (-20 °C to +50 °C)** | | |
| Response unaffected | X | X |
| Operational temperature range (° C) | -20 to +50 | -20 to +40 |
| **Humidity Test (65 % to 93 % at 35 °C)** | | |
| Response unaffected | X | O |
| **Dust Test (IEC 60529 IP53 [35])** | | |
| Response unaffected | X | X |
| **Moisture Test (IEC 60529 IP53 [35])** | | |
| Response unaffected | X | X |

Table 23: Electromagnetic tests for the GSDs. “N” indicates no frequencies with susceptibilities.

| | GSD | |
|---|---|---|
| | **A** | **B** |
| **Electrostatic Discharge Test (up to ±6 kV)** | | |
| Response unaffected | X | X |
| **Radio Frequency (80 MHz to 1 GHz, 1.4 GHz to 2.5 GHz at 20 V/m)** | | |
| Response unaffected | X | X |
| Frequencies with susceptibilities (MHz) | N | N |
| **Radiated Emissions (30 to $>$ 960 MHz at 100 to 500 $\mu$V/m)** | | |
| Emissions lower than maximum allowed | X | X |
| **AC Magnetic Field Test (30 A/m at 50 to 60 Hz)** | | |
| Response unaffected | X | X |
| **DC Magnetic Field Test (10 G)** | | |
| Response unaffected | O | O |

Table 24: Mechanical tests for the GSDs. An “X” is used for ”yes”, and an “O” is used for ”no”.

| | GSD | |
|---|---|---|
| | **A** | **B** |
| **Drop Test (from 0.3 m on a hardwood surface)** | | |
| Instrument free of damage | X | X |
| Response unaffected | X | X |
| **Vibration Test (random vibration, 0.01 $g^2$, 5 and 500 Hz endpoints)** | | |
| Instrument free of damage | X | X |
| Response unaffected | X | X |
| **Impact Test (0.2 J impacts)** | | |
| Instrument free of damage | X | X |
| Response unaffected | X | X |

## 2.4 Test Results for Neutron Search Detectors (NSDs)

A total of four NSDs were tested, two by DNDO and two by the JRC (see Table 25). A complete summary of the test results for the NSDs can be found in references [7] and [8].

Table 25: System information for NSDs. Instruments were tested by DNDO, unless denoted with * for those tested by JRC.

| Manufacturer/Model | Mass | Neutron Sensor | Gamma Sensor | Dimensions (cm) |
|---|---|---|---|---|
| Thermo Scientific RadEye GN in Moderator | 2.6 kg | One $^{6}$Li-doped scintillation detectors | Minuature PMT | 20×16×16 |
| Rotem Industries BAK-2691 | 4.3 kg | Two 5-atmosphere $^{3}$He tubes | *No gamma sensor* | 20×15×30 |
| Atomtex AT05M* | 7.5 kg | Two 2.7-atmosphere $^{3}$He tubes | GM counter | 39×10×17 |
| Baltic KSAR1U.06* | 4.1 kg | Three 2-atmosphere $^{3}$He proportional counters | GM counter | 30×15×12 |

### General Description and Requirements

A summary of the general information for NSDs is shown in Table 26. For the units for which battery performance was tested, the instruments were able to operate in a non-alarming state for well over 8 hours, and had stable sensitivity after 8 hours of operation. The batteries lasted for more than 3 hours in an alarming state for those instruments with alarms. Instruments met almost all requirements for markings and reference points. Displays for all NSDs were readable in low and high lighting conditions. Testers reported that all instruments were simple for non-experts to use.

Table 26: General characteristics of NSDs. An "X" is used if the system has the feature, and an "O" if it does not. "ND" indicates information not provided or that the test was not performed.

| | NSD | | | |
|---|---|---|---|---|
| | **A** | **B** | **C** | **D** |
| Visual and/or audible alarm | O | X | X | X |
| User interface simple and intuitive | X | X | X | X |
| Center of detector specified on front/back of instrument | O | X | X | X |
| Center of detector specified on side of instrument | X | O | O | X |
| Battery lifetime, under continuous alarm conditions: $\geq$ 30 minutes | ND* | X | ND | ND |
| Battery lifetime, under no alarm conditions: $\geq$ 16 hours | X | X | ND | ND |
| Count rate stable over 8 hours of operation | X | X | ND | ND |
| Possible to save data to file | O | X | X | X |
| Data file in ANSI N42.42 format | O | O | O | O |
| Possible to transfer data to computer | O | X | X | X |
| Instrument provides integration mode | X | O | X | X |
| Instrument provides monitor mode | X | X | O | O |
| Instrument provides search mode | X | X | X | X |
| Controls operable with gloves | X | X | X | X |
| Diagnostic capabilities | O | X | X | X |
| Display readable in high and low lighting conditions | X | X | X | X |
| Source indication proportional to radiation field | X | X | X | X |
| Warmup status indicated (during warmup) | O | O | X | X |
| Warms up in less than two minutes | X | X | X | X |
| Fully operational after warmup period completes | X | X | X | X |
| * Instrument does not have alarm capability. | | | | |

**Radiological Tests**

False Alarm Test

Only two instruments, B and C, were tested for false alarms (detector A does not alarm - it only displays neutron count rate). Each of the NSDs tested had three units tested, and the tests ran for at least 8 hours with all three instruments. The number of false alarms observed over the test period are shown in Table 27.

Table 27: False alarm test for the NSDs. For NSDs, results by unit were not included in the detailed report.

| | Units tested | Duration (hours:minutes) | Gamma | Neutron |
|---|---|---|---|---|
| B | 3 | 20:10 | 0 | 1 |
| C | 3 | 8:00 | 0 | 3 |

Gamma Radiation Detection Capabilities

All but one of the NSDs were equipped with a personal protection alarm. None of the detectors reported a neutron alarm in response to a gamma source alone. Instruments A, C, and D successfully responded to the neutron source in the presence of the gamma source, although A did not provide an alarm (it displayed an increase in the count rate readings). NSD B did not alarm with or without the neutron source in this configuration. Details of the gamma rejection tests are shown in Table 28.

Table 28: Gamma interference tests for the NSDs. An "X" is used for "yes," and an "O" is used for "no." "ND" indicates information not provided or that the test was not performed. Detector A did not have alarm capability. Detectors C and D did not have neutron count rate capability.

| | **NSD** | | | |
|---|---|---|---|---|
| | **A*** | **B** | **C** | **D** |
| No alarms for gamma source alone | O | X | X | X |
| Alarm in all trials: gamma + neutron | O | O | X | X |
| * NSD not equipped with an alarm indication. It only displays neutron count rates. | | | | |

Neutron Radiation Detection Capabilities

The responses of the instruments to neutron sources are detailed in Table 29 below. NSD B did not show a noticeable response to neutrons.

Table 29: Neutron radiation tests for the NSDs. “ND” indicates information not provided or that the test was not performed. Detector A did not have alarm capability. Detectors C and D did not have neutron count rate capability.

| | NSD | | | |
|---|---|---|---|---|
| | **A*** | **B** | **C** | **D** |
| **Time to Alarm (neutron source, unmoderated)** | | | | |
| Alarm in all trials: neutron | O | O | X | X |
| Alarm in $\leq$ 2 seconds | O | O | X | X |
| **Time to Alarm (neutron source, 4 cm moderation)** | | | | |
| Alarm in all trials: neutron source | O | O | O | ND |
| Alarm in $\leq$ 2 seconds | O | O | X | ND |
| **Time to Alarm (neutron source, 7.64 cm moderation)** | | | | |
| Alarm in all trials: neutron source | O | ND | O | O |
| Alarm in $\leq$ 2 seconds | O | ND | O | O |
| **Personal Protection Alarm** | | | | |
| Equipped with personal protection alarm | O | X | X | X |
| Alarm in all trials: medium-energy gamma | NA | X | X | X |
| Alarm in all trials: high-energy gamma | NA | X | ND | ND |
| Alarm in all trials: neutron | NA | ND | O | X |
| **Over-Range** | | | | |
| Equipped with over-range indicator | X | X | O | O |
| Indicated over-range in $\leq$ 3 seconds | O | O | NA | NA |
| * NSD not equipped with an alarm indication. It only displays neutron count rates. | | | | |

**Environmental, Electromagnetic, and Mechanical Tests**

Only two of the NSDs, A and B, were tested for environmental, electromagnetic, and mechanical sensitivities. NSD A did well in the temperature tests and mechanical tests, except the drop test. It did not perform well in the electromagnetic tests. NSD B had large fluctuations in the readout that made it difficult to determine whether or not it was sensitive. Test results are shown in Table 30, Table 31, and Table 32.

Table 30: Environmental tests for the NSDs. An "X" is used for "yes", and an "O" is used for "no".

| | NSD | |
|---|---|---|
| | **A** | **B** |
| **Temperature Test (–20 °C to +50 °C)** | | |
| Neutron response unaffected | X | X |
| Operational temperature range for neutrons (°C) | -20 to +40 | +20 |
| **Humidity Test (40 % to 93 % RH at 35 °C)** | | |
| Neutron response unaffected | O | O |
| **Temperature Shock Test (recover in 15-30 min, 20 °C to/from +50 °C, 20 °C to/from -20 °C)** | | |
| Neutron response unaffected | X | O |
| **Cold Temperature Startup Test (start at -20 °C)** | | |
| Neutron response unaffected | X | O |
| **Dust Test (IEC 60529 IP53 [35])** | | |
| Instrument free of dust ingress | X | X |
| Neutron response unaffected | X | O |
| **Moisture Test (IEC 60529 IP53 [35])** | | |
| Instrument free of water ingress | X | O |
| Neutron response unaffected | X | O |

Table 31: Electromagnetic tests for the NSDs. An "X" is used for "yes", and an "O" is used for "no".

| | NSD | |
|---|---|---|
| | **A** | **B** |
| **Electrostatic Discharge Test (up to ±6 kV)** | | |
| Neutron response unaffected | ND | X |
| **Radio Frequency (80 MHz to 1 GHz, 1.4 GHz to 2.5 GHz at 20 V/m)** | | |
| Neutron response unaffected | O | X |
| Frequencies with susceptibilities | 1 MHz, 150 MHz | ND |
| **Radiated Emissions (30 to > 960 MHz at 100 to 500 $\mu$V/m)** | | |
| Emissions lower than maximum allowed | X | X |
| **DC Magnetic Field Test (10 G; 3 orthogonal axes)** | | |
| Neutron response unaffected | O | X |
| **AC Magnetic Field Test (30 A/m 50 Hz; 3 orthogonal axes)** | | |
| Neutron response unaffected | O | X |

Table 32: Mechanical tests for the NSDs. An "X" is used for "yes", and an "O" is used for "no".

| | NSD | |
|---|---|---|
| | **A** | **B** |
| **Drop Test (from 0.3 m onto a wood floor without shipping case)** | | |
| Instrument free of damage | O | X |
| Instrument did not alarm due to drop | O | O |
| Neutron response unaffected | X | X |
| **Drop Test (from 1 m onto a concrete floor in shipping case)** | | |
| Instrument free of damage | X | X |
| Instrument did not alarm due to drop | X | X |
| Neutron response unaffected | X | O |
| **Vibration Test (random vibration, 0.01 $g^2$, 5 and 500 Hz endpoints)** | | |
| Instrument free of damage | X | X |
| Instrument did not alarm due to vibration | X | X |
| Neutron response unaffected | X | X |
| **Impact Test (0.2 J impacts)** | | |
| Instrument free of damage | ND | O[†] |
| Instrument did not alarm due to impact | ND | ND |
| Neutron response unaffected | ND | O |
| [†] One instrument (of two instruments tested) was damaged | | |

## 2.5 Test Results for Radionuclide Identification Devices (RIDs)

Sixteen RID models were tested (three units per model), ten by DNDO and six by the JRC (see Table 33). Thirteen of the RIDs tested are equipped with a neutron detector. A complete summary of the test results for the RIDs can be found in references [9] and [10]. These instruments are not intended to provide an accurate measurement of the ambient dose equivalent rate or exposure rate. However, all do provide an indication of the ambient dose equivalent rate or exposure rate.

Table 33: System information for RIDs. Instruments were tested by DNDO, unless denoted with * for those tested by JRC. ”ND” indicates ”no data” provided.

| Manufacturer/Model | Gamma Sensor | Gamma Ambient Dose Equivalent Rate Range ($\mu$Sv/h) | Gamma Energy Range (MeV) | Neutron Sensor |
|---|---|---|---|---|
| Baltic Scientific Instruments/ Handy-GPD25300* | HPGe | ND | 0.01 - 1.5 | None |
| Berkeley Nucleonics Corp./ BNC 940-2L | LaBr | 0 - 20 | 0.018 - 3 | None |
| Berkeley Nucleonics Corp./ BNC 940-3GN-V8 | NaI | 0 - 20 | 0.018 - 3 | $^{6}$LiI |
| Berkeley Nucleonics Corp./ SAM 940 2”* | 2” NaI | ND | 0.018 - 3 | $^{6}$LiI |
| Berkeley Nucleonics Corp./ SAM 940 3”* | 3” NaI | ND | 0.018 - 3 | $^{6}$LiI |
| Canberra/ Falcon 5000N | HPGe, GM$^{\dagger}$ | ND | 0.02 - 3 | $^{3}$He |
| Canberra/ Inspector 1000 IN1KL-1N* | LaBr, GM$^{\dagger}$ | 0.01 - 10000 | 0.03 - 3 | $^{3}$He |
| FLIR/ ICX IndentiFINDER 2 | NaI, GM$^{\dagger}$ | 0 - 10000 | 0.02 - 3 | $^{3}$He |
| FLIR/ IdentiFINDER 2 ULCS-NGH* | NaI, GM$^{\dagger}$ | 0 - 10000 | 0.02 - 3 | $^{3}$He |
| FLIR/ ICX Raider GN | CZT | 0.05 - 1500 | 0.05 - 3 | $^{3}$He |
| Mirion/ SpiR-ID NaI* | NaI, GM$^{\dagger}$ | 0.01 - 10000 | 0.025 - 3 | LiI(Eu) |
| Nuctech/ RM0100NH | NaI | 0 - 10000 | 0.025 - 3 | $^{3}$He |
| ORTEC/ Micro-detective DX | HPGe, GM$^{\dagger}$ | 0.05 - 10000 | ND | None |
| Polimaster/ PM1410 | NaI | 0.01 - $1\times10^{7}$ | 0.025 - 3 | $^{3}$He |
| Smiths/ Radseeker CL | LaBr | 0.1 - 200 | 0.026 - 3 | $^{3}$He |
| Smiths/ Radseeker CS | NaI | 0.1 - 100 | 0.025 - 3 | $^{3}$He |
| † GM means Geiger Muller tube detector | | | | |

### General Description and Requirements

A summary of general RID characteristics are shown in Table 34. All RIDs, except for one, had two modes of operation: a “routine” where search and radionuclide identification capabilities are available to the user and another “restricted” were settings could be adjusted. Some RIDs had additional modes not required by the standard. All RIDs that had a personal protection alarm had a visual and an audible indication. Some were equipped with a vibration alarm. For most RIDs the alarm could not be acknowledged unless the radiation source was removed, which is a desirable feature for protection of the user. In most cases, the alarm threshold can be adjusted by the user. Most RIDs had more than one way to transmit data to an external computer, the most commonly used technologies for data transmission included: Ethernet, USB, Bluetooth, and removable compact flash memory cards. The controls of most RIDs can be operated using weather protection gloves, and they are designed to minimize accidental operations. Most RIDs' displays could be read in normal, low, and high light conditions, though few could not be read at certain angles. The RIDs instrumented with HPGe detectors took a long time to cool down (using either mechanical or liquid nitrogen cooling). Once cool, start-up from the stand-by position was fast. Few RIDs had the detector location or reference points marked.

Table 34: General characteristics of RIDs. An "X" is used if the system has the feature, and an "O" if it does not. "ND" indicates that there is no data available or the instrument was not tested.

| | RID | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** | **K** | **L** | **M** | **N** | **O** | **P** |
| Routine and restricted operating modes | X | X | X | X | X | X | X | X | X | O | X | X | X | X | X | X |
| External markings | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Transmission of files to external computer | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Data file in ANSI N42.42 format | X | X | X | X | X | X | X | X | X | O | O | X | X | X | O | O |
| Spectral identification file information | X | X | X | X | X | X | X | X | X | O | O | X | X | X | O | O |
| User interface simple and intuitive | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Display readable in low light conditions | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Display readable in high light conditions | X | X | X | X | X | O | X | O | X | X | X | X | X | X | X | O |
| Stabilization time less than 2 min | X | X | X | ND | X | X | O | X | O | O | X | X | O | O | ND | O |
| Certified to operate in explosive atmospheres | O | ND | O | ND | O | O | ND | O | ND | ND | O | O | O | O | ND | O |
| Personal protection alarm | X | X | X | X | X | X | X | X | X | O | X | X | X | X | X | X |
| Low-battery indication | X | ND | X | ND | X | X | ND | X | ND | ND | X | X | X | X | ND | X |
| Use non-rechargeable batteries | X | ND | X | ND | O | X | ND | X | ND | ND | O | O | O | O | ND | O |
| Battery lifetime, over 2 h | X | ND | X | ND | X | X | ND | X | ND | ND | X | X | X | X | ND | X |
| Operates with external DC sources | X | ND | X | ND | X | X | ND | X | ND | ND | X | X | X | X | ND | X |

### Radiological Tests

Radiological tests were performed to test instrument alarm and identification response to both gamma and neutron radiation sources. The following outlines the highlights from these tests.

Gamma Radiation Detection Capabilities

All RIDs were equipped with audible and visual alarms, six were equipped with vibration alarms, and many worked with earphones. All, except one, could setup the alarms via an administrator login. For most RIDs, all except 3, the exposure or ambient dose equivalent rate readings for medium-energy gamma source are within the required range for the reference value. The low-energy gamma source exposure or ambient dose equivalent rate readings tend to be lower than the required range relative to the reference value for most RIDs. Not all RIDs were tested with the high-energy gamma source. For those tested, the exposure or ambient dose equivalent rate readings were within the required range relative to the reference value. Most RIDs did not display a specific over-range indication, instead they displayed different messages such as: warning high field, high dose warning, Danger 9.9.9.9, Danger, Alert, warning high ambient dose equivalent rate, move back, or gamma detector saturated due to high count rate. During the over-range test, two RIDs powered down the detector to prevent damage while displaying “gamma detector saturated due to high count rate” and had to be manually rebooted to return to normal operations. Another RID displayed “no probe”.

Most RIDs detected the medium-energy gamma source, and the time to alarm varied between 0.7 seconds and 28 seconds. Most alarmed in less than 3 seconds, while only a maximum of 2 seconds was allowed.

Summaries of the results of these tests are shown in Table 35.

Table 35: Gamma radiation tests for the RIDs. An “X” is used for “yes”, an “O” is used for “no”, “ND” indicates that there is no data available or the instrument was not tested and “NA” is used for ”not applicable” when RIDs do not have the detection capabilities. Sources of differing energy refer to gamma-ray sources.

| | **RID** | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** | **K** | **L** | **M** | **N** | **O** | **P** |
| **Time to Alarm Gammas (for medium-energy gamma source)** | | | | | | | | | | | | | | | | |
| Alarmed in all trials | X | X | X | X | X | X | X | X | X | NA | X | X | X | X | X | X |
| Time to alarm $\leq$ 2 seconds | X | X | X | O | O | O | O | O | O | NA | O | O | X | X | O | O |
| **Accuracy Gammas ($\pm$ 30 % from reference value at all dose rates)** | | | | | | | | | | | | | | | | |
| Accurate at low-energy | O | X | O | O | O | O | O | O | O | NA | O | O | O | O | O | ND |
| Accurate at medium-energy | X | X | O | X | O | O | X | X | X | NA | O | O | O | X | X | ND |
| Accurate at high-energy | ND | O | ND | O | ND | ND | O | ND | O | NA | ND | ND | ND | ND | O | ND |
| **Over-Range for Gammas (10 times maximum or 1 mSv/h medium-energy gamma source)** | | | | | | | | | | | | | | | | |
| Equipped with over-range indication | X | X | X | O | O | O | O | O | O | NA | X | O | O | O | O | ND |
| Alarm or over-range displayed | X | X | X | X | X | X | X | X | X | NA | X | X | X | X | O | ND |
| Alarm remained until source removed | X | X | X | X | X | X | X | X | X | NA | X | X | X | X | O | ND |
| Returned to normal operation within 5 minutes | X | X | X | X | O | X | X | X | X | NA | X | X | O | O | O | ND |

## Neutron Radiation Detection Capabilities

Three of the RIDs were not equipped with neutron detectors. When exposed to a high gamma radiation field, eight of the neutron detectors did not produce neutron alarms, demonstrating insensitivity of the neutron sensor to gammas. Five still responded to neutrons while the high gamma radiation field was present. All others produced neutron alarms due to the gamma field alone, which is problematic. Most RIDs detected a moderated neutron source, the time to alarm varied between 1 second and 24 seconds. Many of the RIDs did not detect an unmoderated neutron source, with a time to alarm varying between 1 second and 49 seconds.

Summaries of the results of these tests are shown in Table 36.

Table 36: Neutron radiation tests for the RIDs. An "X" is used for "yes", an "O" is used for "no", "ND" indicates that there is no data available or the instrument was not tested and "NA" is used for "not applicable" when RIDs do not have the detection capabilities.

| | RID | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** | **K** | **L** | **M** | **N** | **O** | **P** |
| **Time to Alarm Neutrons (unmoderated and moderated $^{252}$Cf - 2 $\times 10^4$ neutron/s)** | | | | | | | | | | | | | | | | |
| Alarmed in all trials: unmoderated source | O | ND | O | ND | O | NA | O | O | O | NA | O | NA | X | X | ND | O |
| Time to alarm $\leq$ 2 seconds | O | O | O | O | O | NA | O | O | O | NA | O | NA | O | O | O | O |
| Alarmed in all trials: moderated source | X | ND | X | ND | X | NA | ND | ND | ND | NA | O | NA | X | X | ND | X |
| Time to alarm $\leq$ 2 seconds | O | ND | O | ND | O | NA | ND | ND | ND | NA | O | NA | O | O | ND | X |
| **Neutron Indication in the Presence of Photons (gamma medium-energy source at 100 $\mu$Sv/h)** | | | | | | | | | | | | | | | | |
| No neutron response with gamma source only | X | X | X | X | X | NA | O | O | O | NA | O | NA | X | X | X | O |
| Neutron response with both gamma and neutron sources | O | X | O | X | O | NA | ND | ND | ND | NA | ND | NA | X | X | X | ND |

Radionuclide Identifications

All, except two of the RIDs, had the required radionuclide library and its associated categories. When performing an identification of background, all except three of the RIDs, identified NORM or no radionuclides. When tested with a radionuclide that is not part of the RIDs library, only two of the RIDs reported "Unknown", and the rest of the RIDs identified different radionuclides.

Most RIDs could correctly identify the industrial, NORM, and HEU sources, but most of them had problems identifying WGPu and medical sources. The RID L identified most radionuclides correctly. In some cases, the identification of shielded materials improved with respect to the bare sources. Four of the RIDs showed a good identification performance against mixed gamma sources and masking test cases.

Most RIDs correctly identified low-energy, medium-energy, and high-energy gamma sources for angles of incidence between -45°C and +45°C in the vertical and horizontal planes. Most of the exposure rate or ambient dose equivalent rate responses are within the acceptance range, except for the low-energy gamma source at several angles for which the RIDs under respond by factors of up to 40 %.

When exposing the RIDs to a radiation field that is 90 % and 120 % from the maximum ambient dose equivalent rate value for identification, five of the RIDs displayed a message to move back due to a high radiation field, and most of the RIDs correctly identified the radionuclide. When a NORM field was used to assess the interference in identifying certain radionuclides, most RIDs correctly identified the radionuclides of interest. When a beta emitting source was used to interfere with the identification of a gamma source, seven of the RIDs were able to identify both the radionuclide of interest and the presence of a beta radiation field. Most of the other RIDs identified only the radionuclide of interest when the beta field was present. Fifteen of the RIDs could identify a radionuclide when surrounded by interfering surrounding material.

**Environmental, Electromagnetic, and Mechanical Tests**

Summaries of the results of these tests are shown in Tables 37, 38, and 39. These tests were not performed for the RIDs tested at the JRC. Several tested by DNDO were not available due to damage or by request of the manufacturer. Most RIDs worked properly over the entire temperature range, though few had problems operating at low temperatures. When the RIDs were moved from room temperature to -20°C or 50°C, most worked correctly for the first 15 minutes, but the identification performance degraded with time as the RIDs were exposed to these extreme temperatures for up to 1 hour. Most RIDs showed no dust or water penetration, dust and water did not affected the RIDs' response. Several RIDs are not susceptible to radio frequency interference. For those that displayed susceptibilities, they occur at different frequencies. Half of the RIDs did not produce radiated emissions that can interfere with the operations on neighboring devices. In general, RIDs were affected by DC magnetic fields. Most were affected by the vibration and mechanical tests. Few were not damaged by the drop test. Most were not affected by the mechanical impacts.

Table 37: Environmental tests for the RIDs. An "X" is used for "yes", an "O" is used for "no", and "ND" indicates that there is no data available or the instrument was not tested.

| | **RID** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **C** | **E** | **F** | **H** | **K** | **L** | **M** | **N** | **P** |
| **Temperature Test (-20°C to +50°C)** | | | | | | | | | | |
| Gamma response unaffected | X | O | O | X | O | X | ND | X | O | ND |
| Neutron response unaffected | X | X | X | X | X | ND | ND | X | X | ND |
| Operational temperature range for gammas (°C) | -20 to 50 | 0 to 40 | 20 to 40 | -20 to 40 | 0 to 50 | -20 to 50 | ND | -20 to 50 | 0 to 50 | ND |
| Operational temperature range for neutrons (°C)* | -20 to 50 | -20 to 50 | -20 to 50 | -20 to 50 | -20 to 50 | ND | ND | -10 to 50 | -20 to 50 | ND |
| **Humidity Test (40 % to 93 % RH at 35°C)** | | | | | | | | | | |
| Gamma response unaffected | X | X | X | O | ND | ND | ND | X | O | ND |
| Neutron response unaffected | X | X | X | O | ND | ND | ND | O | O | ND |
| **Temperature Shock Test (recover in 15-30 min, 20°C to/from +50°C, 20°C to/from -20°C)** | | | | | | | | | | |
| Gamma response unaffected | O | O | O | O | O | ND | ND | X | X | ND |
| Neutron response unaffected | X | X | X | X | O | ND | ND | X | X | ND |
| **Cold Temperature Startup Test (start at -20°C)** | | | | | | | | | | |
| Gamma response unaffected | O | O | O | O | ND | ND | ND | X | X | ND |
| Neutron response unaffected | O | X | X | O | ND | ND | ND | X | X | ND |
| **Dust Test (IEC 60529 IP53 [35])** | | | | | | | | | | |
| Instrument free of dust ingress | X | X | X | ND | X | ND | ND | X | X | ND |
| Gamma response unaffected | X | O | X | X | X | ND | ND | X | X | ND |
| Neutron response unaffected | X | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| **Moisture Test (IEC 60529 IP53 [35])** | | | | | | | | | | |
| Instrument free of water ingress | O | X | X | ND | ND | ND | ND | X | X | ND |
| Gamma response unaffected | X | X | X | X | ND | ND | ND | X | X | ND |
| Neutron response unaffected | X | ND | ND | ND | ND | ND | ND | ND | ND | ND |
| * Only the neutron alarm was verified for this test. | | | | | | | | | | |

Table 38: Electromagnetic tests for the RIDs. An "X" is used for "yes", an "O" is used for "no", "N" for "none" worked correctly for all frequencies, "BR" is used for "broad range", and "ND" indicates that there is no data available or the instrument was not tested'.

| | RID | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **C** | **E** | **F** | **H** | **K** | **L** | **M** | **N** | **P** |
| **Electrostatic Discharge Test (up to ±6 kV conductive surfaces and coupling planes)** | | | | | | | | | | |
| Gamma response unaffected | X | O | X | X | O | X | ND | X | X | ND |
| Neutron response unaffected | O | X | X | O | O | X | ND | X | X | ND |
| **Radio Frequency (80 MHz to 2.5 GHz at 10 V/m)** | | | | | | | | | | |
| Gamma response unaffected | X | X | X | O | O | O | ND | X | X | ND |
| Neutron response unaffected | X* | X | X | O | X | O | ND | X | X | ND |
| Frequencies with susceptibilities (MHz) | N | N | N | BR | BR | BR | ND | N | X | ND |
| **Radiated Emissions (from 30 to above 960 MHz at 100 to 500 $\mu$V/m)** | | | | | | | | | | |
| Emissions lower than maximum allowed | X | X | O | O | O | O | ND | X | X | ND |
| **DC Magnetic Field Test (10 G; 3 orthogonal axes)** | | | | | | | | | | |
| Gamma response unaffected | O | X | O | O | O | X | ND | X | X | ND |
| Neutron response unaffected | O | X | X | O | O | X | ND | X | O | ND |
| * 1 of the 3 units showed gamma susceptibilities between 80 and 1000 MHz. | | | | | | | | | | |

Table 39: Mechanical tests for the RIDs. An “X” is used for “yes”, an “O” is used for “no”, and “ND” indicates that there is no data available or the instrument was not tested.

| | RID | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **C** | **E** | **F** | **H** | **K** | **L** | **M** | **N** | **P** |
| **Vibration Test (random vibration, 0.01 $g^2$/Hz, 5 and 500 Hz endpoints)** | | | | | | | | | | |
| Instrument free of damage | O* | X | X | X | X | O | ND | X | X | ND |
| Instrument did not alarm due to vibration | X | O | ND | ND | ND | ND | ND | X | X | ND |
| Gamma response unaffected | X | O | X | X | O | O | ND | X | X | ND |
| Neutron response unaffected | X | X | X | O | O | O | ND | X | O | ND |
| **Mechanical Shock Test (pulses of 50 g, 18 ms, 3 orthogonal axes)** | | | | | | | | | | |
| Instrument free of damage | O | X | X | ND | ND | ND | ND | X | X | ND |
| Instrument did not alarm due to shock | O | X | O | ND | ND | ND | ND | O | O | ND |
| Gamma response unaffected | O | X | O | ND | ND | ND | ND | X | O | ND |
| Neutron response unaffected | O | X | O | ND | ND | ND | ND | O | O | ND |
| **Impact Test (0.2 J impacts)** | | | | | | | | | | |
| Instrument free of damage | X | X | X | X | X | X | ND | X | X | ND |
| Instrument did not alarm due to impact | O | X | X | X | X | ND | ND | X | O | ND |
| Gamma response unaffected | X | X | X | X | X | X | ND | X | X | ND |
| Neutron response unaffected | X | X | X | X | X | O | ND | O | O | ND |
| **Drop Test (from 1.5 m on a concrete floor)** | | | | | | | | | | |
| Instrument free of damage | O | X* | O | ND | ND | ND | ND | X | X | ND |
| Gamma response unaffected | O | X | O | ND | ND | ND | ND | X | X | ND |
| Neutron response unaffected | ND | X | O | ND | ND | ND | ND | O | X | ND |
| * the units switched off during test. | | | | | | | | | | |

## 2.6 Test Results for Backpack Radiation Detectors (BRDs)

Seven BRD models were tested (between one and three units per model), four by DNDO and three by the JRC (see Table 40). A complete summary of the test results for the BRDs can be found in reference [11] and [12]. These instruments are not intended to provide an accurate measurement of the ambient dose equivalent rate or exposure rate. For most BRD models, one unit was available for testing. In some cases, two or three units were available (BRD B and A respectively), as submitted by the manufacturers.

Table 40: System information for BRDs. Instruments were tested by DNDO, unless denoted with * for those tested by JRC. "ND" indicates "no data" provided.

| Manufacturer/Model | Weight (kg) | Gamma Sensor | Neutron Sensor | Radionuclide Identification | GPS |
|---|---|---|---|---|---|
| Environics Oy/ RanidPro200* | 6.9 | $LaBr_3$ or NaI(Tl) | $^{6}$Li:ZnS (Ag) | Yes | No |
| Innovative American Technology/ BRND | 13 | NaI(Tl) | $^{6}$Li | Yes | No |
| MEET Instruments G.m.b.H (Atomtex)/ AT6101C* | 7 | Plastic scintillator and NaI(Tl) | $^{3}$He | Yes | Yes |
| Proportional Technologies, Inc/ PTI | 5.5 | NaI(Tl) | Boron-coated straw | No | No |
| Sensor Technology Engineering Inc/ Radpack | 6.4 | CsI | $^{3}$He | No | No |
| Thermo Fisher Scientific GmbH/ FHT 1377-1 PACKEYE* | 6.8 | Plastic scintillator | $^{3}$He | Distinguishes between natural and artificial radiation | Yes |
| Thermo Scientific/ Packeye | 6.8 | Plastic scintillator | $^{3}$He | Natural background rejection | No |

### General Description and Requirements

A summary of general BRD characteristics are shown in Table 41. Most BRDs had displays that were easy to use. Except for one, all use rechargeable batteries. For most BRDs, the battery lifetime is over 8 hours. Displays were readable with low and high light conditions. All BRDs' appearance was inconspicuous to the casual observer, as they looked like regular backpacks that people could carry with their personal belongings. For most BRDs, switches could be operated using weather protection type gloves.

Table 41: General characteristics of BRDs. An "X" is used if the system has the feature, and an "O" if it does not. "ND" indicates that there is no data available or the instrument was not tested.

| | BRD | | | | | | |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G |
| BRD appears inconspicuous to casual observer | X | X | X | X | X | X | X |
| BRD weight appears to be balanced | X | X | X | X | X | X | X |
| Alarm setting limited to authorized use | X* | X* | X | X | X | X | X* |
| Audible alarm can be muted | X | X | X | X | ND | ND | X |
| Data file in ANSI N42.42 format | O† | O† | O | O | O | X | X |
| Markings | X | X | X | X | O | X | O |
| Switches can be operated when wearing gloves | X | X | X | O | X | O | X |
| Energy and ambient dose equivalent rate ranges provided | O | X | X | X | O | X | O |
| User interface simple and intuitive | X | X | X | X | X | X | X |
| Display readable in low light conditions | X | X | X | X | X | X | X |
| Display readable in high light conditions | X | X | X | O | X | X | X |
| Operating parameters provided | O | X | O | X | O | X | X |
| Certified to operate in explosive atmospheres | O | O | O | O | O | O | O |
| Diagnostics (other than low-battery) | O | O | O | X | O | X | O |
| Low-battery indication | X | X | ND | ND | X | ND | X |
| Use non-rechargeable batteries | X | O | ND | ND | O | ND | O |
| Battery lifetime, over 8 h | X | X | ND | ND | X | ND | O |
| Operates with external DC sources | O | X | ND | ND | X | ND | X |
| BRD batteries are hot-swappable | X | O | ND | ND | O | ND | O |
| * Can only be set by manufacturer. † No files are produced. | | | | | | | |

### Radiological Tests

Radiological tests were performed to test instrument alarm and identification (when applicable) response to both gamma and neutron radiation sources. The following outlines the highlights from these tests.

False Alarm Test

The BRDs are designed for search of small sources so are constantly displaying an indication even at background levels. The indication level is proportional to the intensity of the radiation field. The false alarm rate of the BRDs was tested at the background radiation level of the test location. Five displayed less than 5 alarms in 10 hours of operation at background radiation level. Two displayed a large number of false alarms, as their alarm threshold may be set very low. A summary of these results can be found in Table 42.

Table 42: Total number of gamma (including identifications, when applicable) and neutron alarms for each BRD unit tested. The time duration of the test is per unit is expressed in hours. “ND” indicates that there is no data available or the instrument was not available for the test.

| BRD | Time (h) | Gamma Alarms Unit | | | Neutron Alarms Unit | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 1 | 2 | 3 |
| A | 10 | 11 | 102 | 166 | 174 | 96 | 123 |
| B | 10 | 1 | 1 | ND | 1 | 2 | ND |
| C | 10 | 3 | ND | ND | 0 | ND | ND |
| D | 10 | 4 | ND | ND | 0 | ND | ND |
| E | 10 | 24 | ND | ND | 191 | ND | ND |
| F | 10 | 0 | ND | ND | 0 | ND | ND |
| G | 10 | 0 | ND | ND | 0 | ND | ND |

Gamma Radiation Detection Capabilities

The gamma response of the BRDs was tested using four sources moving past the BRD at a speed of 1.2 m/s at different angles both in the vertical and horizontal plane (360° angles) to check for the response in all directions. All BRDs, except for two, had problems detecting the low-energy gamma source in all directions. All were able to detect all other sources, except for BRD F that rarely detected any source. The time to alarm was less than 2 seconds for most cases with few exceptions.

The gamma-ray accuracy test was performed for the BRDs tested at the JRC, the readings were within the expected range for all the reference radiation fields used for the test. One of the BRDs displayed the overload indication at the maximum radiation field value. Only two BRD models have a personal protection alarm, for one, all the LEDs were lit at the same time, and for the other, a message saying “exceeding personal protection alarm” was displayed.

BRDs D, E, and F did not have an over-range display or the manufacturer did not provide the maximum range of operation. BRDs B, C, and G provided an over-range indication and worked properly as required by the standard. BRD A readings saturated at a lower value than what it was exposed to and did not display an over-range indication. This poses a risk to the users if exposed to a sudden high radiation field (it might not be an issue if the field increases slowing, and the user notices when the value saturates).

For the slow approaching gamma source (gradually increasing gamma radiation level), BRD E was not tested. All other BRDs, except BRD F, detected the source as expected. BRDs B and C were the only instruments that could alert the user of a change in the gamma radiation background, as these BRDs had background rejection capabilities.

Summaries of the results of these tests are shown in Table 43.

Table 43: Gamma radiation tests for the BRDs. An “X” is used for “yes”, an “O” is used for “no”, “ND” indicates that there is no data available or the instrument was not tested and “NA” is used for “not applicable” when BRDs do not have the detection capabilities. Sources of differing energy refer to gamma-ray sources.

| | **BRD** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** |
| **Time to Alarm Gammas (for HEU-like, low-, medium- and high-energy gamma sources)** | | | | | | | |
| Alarmed in all trials: low-energy | O | O | O | O | O | O | O |
| Time to alarm $\leq$ 2 seconds | X | X | ND | ND | X | ND | O |
| Alarmed in all trials: medium-energy | X | X | X | X | X | O | X |
| Time to alarm $\leq$ 2 seconds | X | X | ND | ND | X | ND | O |
| Alarmed in all trials: high-energy | X | X | X | X | X | O | X |
| Time to alarm $\leq$ 2 seconds | X | O | ND | ND | O | ND | X |
| Alarmed in all trials: HEU-like | X | X | O | O | X | O | X |
| Time to alarm $\leq$ 2 seconds | O | X | ND | ND | X | ND | X |
| **Accuracy Gammas ($\pm$ 30 % from reference value at all dose rates)** | | | | | | | |
| Accurate: medium-energy | NA | ND | X | X | NA | X | O |
| **Over-Range for Gammas (10 times maximum or 1 mSv/h medium-energy gamma source)** | | | | | | | |
| Equipped with over-range indication | O | X | X | O | O | O | X |
| Alarm or over-range displayed | O | X | X | NA | NA | NA | X |
| Remain in alarm until source removed | O | X | X | NA | NA | NA | X |
| Return to normal operation within 60 seconds | O | X | X | NA | NA | NA | X |
| **Gradually Increasing Gamma Radiation Level (medium-energy gamma source, 0.12 m/s speed)** | | | | | | | |
| Alarmed in all trials | X | X | X | X | ND | O | X |
| **Personal Protection Alarm (30 % above alarm threshold value medium-energy gamma source)** | | | | | | | |
| Equipped with a personal protection alarm | O | O | X | X | O | O | O |
| Alarmed in all trials | NA | NA | X | X | NA | NA | NA |
| Time to alarm $\leq$ 2 seconds | NA | NA | X | X | NA | NA | NA |

Neutron Radiation Detection Capabilities

The neutron response of the BRDs was tested using moderated and unmoderated neutron sources moving passed the BRD at a speed of 1.2 m/s at different angles both in the vertical and horizontal plane (360° angles) to check for the response in all directions. The BRDs tested by DNDO rarely detected both moderated and unmoderated neutron sources with the exception of BRD A. The BRDs tested at the JRC produced more neutron alarms (between 3 % and 42 %) for both moderated and unmoderated neutron sources compared to those tested in the US. Most BRDs alarmed in more than 5 seconds, fewer alarms were observed in less than 2 seconds. BRD F never alarmed, BRDs B and E almost never alarmed, BRD A alarmed approximately 50 % of the time, BRD D alarmed between 5 % and 64 % of the time depending on the source and orientation and BRD C alarmed less than 31 % of the time.

Most BRDs did not produce neutron alarms when exposed to an intense gamma radiation field, except for BRD F and some units of BRD A for which there were neutron alarms when the gamma radiation field was present without any neutron sources present. The BRDs that did not trigger a neutron alarm due to the gamma source alone, alarmed to the neutron source while the gamma radiation field was present.

For the slow approaching neutron source (gradually increasing gamma radiation level), BRD E was not tested. Three BRDs (A, C, and D) produced neutron alarms all other BRDs did not alarm.

Summaries of the results of these tests are shown in Table 44.

Table 44: Neutron radiation tests for the BRDs. An “X” is used for “yes”, an “O” is used for ”no”, “ND” indicates that there is no data available or the instrument was not tested and “NA” is used for “not applicable” when BRDs do not have the detection capabilities. Neutron sources of differing moderation refer to as moderated and unmoderated sources.

| | BRD | | | | | | |
|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** |
| **Time to Alarm Neutrons (unmoderated and moderated $^{252}$Cf - 2 $\times 10^4$ neutron/s)** | | | | | | | |
| Alarmed in all trials: unmoderated source | O | O | O | O | O | O | O |
| Time to alarm $\leq$ 2 seconds | O | O | O | O | O | O | O |
| Alarmed in all trials: moderated source | O | O | O | O | O | O | O |
| Time to alarm $\leq$ 2 seconds | O | O | O | O | O | O | O |
| **Neutron Indication in the Presence of Photons (gamma medium-energy source at 100 $\mu$Sv/h)** | | | | | | | |
| No neutron response with gamma source only | O | X | X | X | X | O | O |
| Neutron response with both gamma and neutron sources | NA | X | X | O | ND | NA | ND |
| **Gradually Increasing Neutron Radiation Level (moderated source, 0.12 m/s speed)** | | | | | | | |
| Alarmed in all trials | X | O | O | X | ND | O | O |

Radionuclide Identifications

Three BRDs had radionuclide identification capabilities (BRDs D, F, and G), while two BRDs provided radionuclide categorization (BRDs B and C). These two BRDs divided the gamma radiation detected into levels: Low energy, High energy, and Anomalous radiation. No indication was provided when the detection was associated with a radionuclide that was considered a NORM.

For the single radionuclide identification test, two of the BRDs (D and G) were able to identify most industrial sources 100 % of the time, but they had problems identifying some of the medical and NORM radionuclides. SNM was identified between 50 % and 100 % of the time. BRD F identification performance was different than for the other two BRDs, with probabilities between 20 % and 87 % for industrial sources, between 80 % and 100 % for medical sources, and low probability ($\leq$3 %) for NORM and SNM (i.e., HEU and WGPu). The identification of shielded industrial sources for all three BRDs varied between 80 % and 100 %. The BRDs had problems identifying the radionuclide of interest in most of the masking and simultaneous sources identification test cases.

For the BRD with radionuclide categorization capability, all the medical, industrials, and SNM sources produced Low energy indication, except for the high-energy gamma source for which a High energy together with Anomalous Radiation was indicated. For the NORM source, there were no radionuclide categorization indications, except for 1 trial with one source for which the BRD indicated “High energy”. For the masking and simultaneous sources test cases, most of the indications were Low energy with few Anomalous Radiation and High Energy indications.

During the over-load test, two of the BRDs (D and F) were not able to identify the radionuclide of interest most of the time. When transitioning from the low to the high background radiation level BRDs D, F, and C alarmed (BRD G was not tested). While at the high background level, BRD D identified the radionuclide of interest 100 % of the time, BRD F 63 % of the time and BRD C categorized it as Low energy 60 % of the time.

**Environmental, Electromagnetic, and Mechanical Tests**

Summaries of the results of these tests are shown in Tables 45, 46, and 47. These tests were not performed for BRDs tested at the JRC. Two out of the four BRDs tested by DNDO were not tested against these requirements by request of the manufacturer. For the remaining two BRDs, some of the tests were also not performed by request of the manufacturer. Although, the BRDs did not work as expected for the entire temperature range, they worked correctly for the entire humidity test. The radiated emissions of the BRDs are below the levels that could affect the operation of neighboring electronic devices. Both BRDs were susceptible to radio frequency interferences. For the drop test, BRD B displayed gamma and neutron alarms and high count rate on impact but continued to work properly after the six drops. For the vibration test, the BRD B battery light came on, and there were several gamma alarms.

Table 45: Environmental tests for the BRDs. An “X” is used for “yes”, an “O” is used for “no”, and “ND” indicates that there is no data available or the instrument was not tested.

| | BRD | |
|---|---|---|
| | **A** | **B** |
| **Temperature Test (-20 °C to +50 °C)** | | |
| Gamma response unaffected | O | O |
| Neutron response unaffected | O | X |
| Operational temperature range for gammas (°C) | -10 to 50 | -20 to 40 |
| Operational temperature range for neutrons (°C) | -10 to 50 | -20 to 50 |
| **Humidity Test (40 % to 93 % RH at 35 °C)** | | |
| Gamma response unaffected | X | X |
| Neutron response unaffected | X | X |
| **Cold and Hot Temperature Startup Test (start at -20 °C and +50 °C)** | | |
| Gamma response unaffected cold | O | X |
| Neutron response unaffected cold | O | X |
| Gamma response unaffected hot | X | X |
| Neutron response unaffected hot | X | X |
| **Dust Test (IEC 60529 IP54 [35])** | | |
| Instrument free of dust ingress | ND | X |
| Gamma response unaffected | ND | X |
| Neutron response unaffected | ND | X |
| **Moisture Test (IEC 60529 IP54 [35])** | | |
| Instrument free of water ingress | ND | X |
| Gamma response unaffected | ND | X |
| Neutron response unaffected | ND | X |

Table 46: Electromagnetic tests for the BRDs. An “X” is used for “yes”, an “O” is used for “no”, “BR” is used for “broad range” and “ND” indicates that there is no data available or the instrument was not tested.

| | BRD | |
|---|---|---|
| | **A** | **B** |
| **Electrostatic Discharge Test (up to ±6 kV conductive surfaces and coupling planes)** | | |
| Gamma response unaffected | ND | ND |
| Neutron response unaffected | ND | ND |
| **Radio Frequency (80 MHz to 1 GHz at 50 V/m, 1 GHz to 6 GHz 3 V/m)** | | |
| Gamma response unaffected | O | O |
| Neutron response unaffected | O | O |
| Frequencies with susceptibilities (MHz) | BR | 80 to 434 |
| **Radiated Emissions (from 30 to above 960 MHz at 100 to 500 $\mu$V/m)** | | |
| Emissions lower than maximum allowed | X | X |
| **DC Magnetic Field Test (10 Gauss; 3 orthogonal axes)** | | |
| Gamma response unaffected | X | O |
| Neutron response unaffected | X | X |

Table 47: Mechanical tests for the BRDs. An “X” is used for “yes”, an “O” is used for “no” and “ND” indicates that there is no data available or the instrument was not tested.

| | BRD | |
|---|---|---|
| | **A** | **B** |
| **Vibration Test (random vibration, 0.01 $g^2$/Hz, 5 and 500 Hz endpoints)** | | |
| Instrument free of damage | ND | X |
| Instrument did not alarm due to vibration | ND | O |
| Gamma response unaffected | ND | O |
| Neutron response unaffected | ND | X |
| **Mechanical Shock Test (pulses of 50 g, 18 ms, 3 orthogonal axes)** | | |
| Instrument free of damage | X* | X |
| Instrument did not alarm due to shock | X* | X |
| Gamma response unaffected | X* | X |
| Neutron response unaffected | X* | X |
| **Impact Test (0.2 J impacts)** | | |
| Instrument free of damage | ND | X |
| Instrument did not alarm due to impact | ND | X |
| Gamma response unaffected | ND | X |
| Neutron response unaffected | ND | X |
| **Drop Test (from 1.5 m on a concrete floor)** | | |
| Instrument free of damage | ND | X |
| Gamma response unaffected | ND | O |
| Neutron response unaffected | ND | O |
| * Tested with 4 g, 11 ms pulses upon request from manufacturer. | | |

## 2.7 Test Results for Mobile Systems

A total of four Mobiles were tested (see Table 48) by DNDO. No Mobiles were tested at the JRC. A complete summary of the test results for the mobile systems can be found in reference [13].

Table 48: System information for Mobiles. Instruments were tested by DNDO. “ND” indicates that there is no data available.

| Manufacturer/Model | Gamma Sensor | Gamma Range (MeV) | Neutron Sensor |
|---|---|---|---|
| Raytheon Mobile Nuclear Radiation Detector System | NaI | 0.025−3 | $^3$He |
| Ortec Detective 200 | HPGe | ND | None |
| Thermo Scientific Aris 2 | NaI+PVT | ND | $^3$He |
| Radiation Solutions, Inc RS-700 | NaI(Tl) | 0.015−3 | $^3$He |

Parameters used for testing are listed in Table 49. Five heights were used for the main detection and identification tests. Data was taken in both static mode, with sources stationary in front of the instruments, and dynamic mode, with sources passing by at a fixed speed.

Table 49: Summary of required test parameters for the Mobiles.

| Parameter | Mobile |
|---|---|
| Bottom height (m) | 1.0 |
| Mid-bottom height (m) | 1.5 |
| Middle height (m) | 2.0 |
| Mid-top height (m) | 2.5 |
| Top height (m) | 3.0 |
| Speed (m/s) | 2.2 |
| Static dwell time (s) | 60 |

**General Description and Requirements**

A summary of the general description and requirements for Mobiles is shown in Table 50. Most systems had the required characteristics, though the data format of most was not compliant with the ANSI N42.42 standard [34].

**Radiological Tests**

Radiological tests were performed to test instrument alarm response to both gamma and neutron radiation sources, as well as identification abilities. The following outlines the highlights from these tests.

False Alarm Test

The instruments were observed in a stationary state for a period that was equivalent to the time required to completely monitor 1000 objects, which is approximately 3 hours. A summary of the results is shown in Table 51, which illustrates a fairly low number of false alarms across all Mobiles.

Table 50: General characteristics of Mobiles. An "X" is used if the system has the feature, and an "O" if it does not. "ND" indicates that there is no data available or the instrument was not tested. "NA" is used for "not applicable" when Mobiles do not have the required capabilities.

| | Mobile | | | |
|---|---|---|---|---|
| | **A** | **B** | **C** | **D** |
| Identify radionuclides | X | X | X | X |
| Occupancy sensor | X | O | NA | O |
| Speed sensor | O | O | NA | O |
| Statement of enclosure classification | X | O | O | O |
| External markings permanently fixed | X | X | X | X |
| Measure a static or moving object | X | X | X | X |
| Measure a static object with monitor moving | X | X | X | X |
| Mode (static/dynamic) user-selectable | X | X | X | X |
| Capture photo or video | ND | ND | ND | ND |
| Measure speed | | X | X | X |
| Test without radiation sources | X | X | X | X |
| Operate on internal battery supply | O | X | O | O |
| If able, operate on battery for 3 hour | NA | ND | NA | NA |
| Internally store at least 3 hours of continuous measurement data | X | X | X | X |
| Locally store time-history data | O | X | X | X |
| Transfer user-selected portions of the time-history data to a peripheral device | O | X | X | X |
| Transfer data to external device | X | X | X | X |
| Data format as defined in the ANSI N42.42 standard | O | O | O | X |
| Wireless capabilities | ND | O | O | O |
| Transfer protocol described in manuals | ND | X | X | X |
| Access to controls/adjustments that affect calibration/alarm settings limited to authorized users | X | X | X | X |
| Indication for background changes that can affect overall sensitivity | X | O | X | X |
| Documentation provided | X | X | X | X |

Table 51: False alarm test for the Mobiles

| **Mobile** | **Duration (hours)** | **Gamma alarms** | **Neutron alarms** | **Non-background IDs** |
|---|---|---|---|---|
| A | 3 | 0 | 0 | 0 |
| B | 3 | 1 | 0 | 1 |
| C | 3 | 1 | 0 | 0 |
| D | 3 | 0 | 1 | 0 |

### Gamma Radiation Detection Capabilities

Results are shown in Table 52. The gamma alarm function of the instruments was tested with an array of radionuclides at five heights specified in Table 49, as stationary in front of the instrument (static mode) and passing by the instrument (dynamic mode). Overall, the instruments displayed a significant increase in alarm probability in static mode. This is a potential problem for these instruments as their main purpose is to detect radionuclides while moving. Mobile D alarmed in at least 59 out of 60 trials for all heights and sources in static mode in its event file, but this behavior was not the same in the operator display, with the percentage of heights and sources achieving this metric dropping to as low as $\sim$ 80 %. For the other instruments, at least 59 alarms out of 60 trials was achieved in higher than 75 % of the test configurations only in static mode in the operator display. All other modes (static in the event files and dynamic in both the files and operator display) indicated 59 alarms out of 60 trials in less than $\sim$ 50 % of the heights and source configurations.

Table 52: Gamma radiation tests for the Mobiles. An "X" is used for "yes", and an "O" is used for "no". "ND" indicates that there is no data available or the instrument was not tested. Data are from the operator display only. Data from the middle height only is given for the Response to Gamma Radiation. For information recorded in event files or data from other heights, see Ref. [13].

| | **Mobile** | | | |
|---|---|---|---|---|
| | **A** | **B** | **C** | **D** |
| **Response to Gamma Radiation: Dynamic (alarm in $\geq$ 59 of 60 trials)** | | | | |
| Alarm: HEU-like | X | O | O | X |
| Alarm: WGPu-like | O | O | O | O |
| Alarm: low-energy | X | X | O | X |
| Alarm: medium-energy | X | X | O | X |
| Alarm: high-energy | O | O | O | X |
| Alarm: NORM | O | O | X | O |
| **Response to Gamma Radiation: Static (alarm in $\geq$ 59 of 60 trials)** | | | | |
| Alarm: HEU-like | X | X | O | X |
| Alarm: WGPu-like | X | X | X | X |
| Alarm: low-energy | X | X | O | X |
| Alarm: medium-energy | X | X | O | X |
| Alarm: high-energy | X | X | O | X |
| Alarm: NORM | X | X | X | X |
| **Over-Range (1.5$\times$ maximum or 100 $\mu$Sv/h medium-energy source)** | | | | |
| Equipped with over-range indication | O | O | O | O |
| Alarm in over-range conditions | X | X | ND | O |
| Alarm remained until source removed | X | ND | ND | O |
| Returned to normal operation within 1 minute | X | X | ND | O |

Although no Mobile was equipped with a separate overload indication, Mobiles A and B alarmed and recovered within one minute after removing a source with a high radiation field. Mobile D only alarmed in one of three trials. Excluding Mobile A, the Mobiles tested for their ability to detect changes in background levels performed adequately in nearly all trials.

Neutron Radiation Detection Capabilities

Results are shown in Table 53 for Mobiles A, C, and D. Mobile B was not equipped with a neutron detector. The neutron alarm function of the instruments was tested with both unmoderated and moderated neutron sources at five heights specified in Table 49, as stationary in front of the instrument (static mode) and passing by the instrument (dynamic mode). Overall, the instruments displayed a significant increase in alarm probability in static mode (nearly a factor of 6), with two Mobiles, A and D, alarming in at least 59 out of 60 trials for all heights and sources in static mode in its event file. However, this behavior for Mobiles A and D was not the same in the operator display, with the percentage of heights and sources achieving this metric dropping to as low as $\sim 50$ % in this mode. Mobile C did not meet the 59 alarms out of 60 trials criteria in any height for either source. In fact, its probability to alarm was nearly zero in dynamic mode and increased to only $\sim 30$ % in static mode (operator display only; probability in the event files remained near zero). For the two Mobiles, A and D, that performed well in static mode, performed quite poorly in dynamic mode, with the probability to alarm only around 10 %.

Table 53: Neutron radiation tests for the Mobiles. An "X" is used for "yes", and an "O" is used for "no". "ND" indicates that there is no data available or the instrument was not tested. Data are from the operator display only. Data from the middle height only is given for the Response to Neutron Radiation. For information recorded in event files or data from other heights, see Ref. [13].

| | **Mobile** | | |
|---|---|---|---|
| | **A** | **C** | **D** |
| **Response to Neutron Radiation: Dynamic (alarm in $\geq$ 59 of 60 trials)** | | | |
| Alarm: Moderated | O | O | O |
| Alarm: Unmoderated | O | O | O |
| **Response to Neutron Radiation: Static (alarm in $\geq$ 59 of 60 trials)** | | | |
| Alarm: Moderated | ND | O | O |
| Alarm: Unmoderated | X | O | X |
| **Neutron Indication in Presence of Photons (medium-energy gamma source at 100 $\mu$Sv/h, unmoderated neutrons)** | | | |
| No neutron response: gamma source | ND | ND | X |
| Neutron response: neutron and gamma sources | ND | ND | X |
| **Neutron Indication in Presence of Photons (medium-energy gamma source at 100 $\mu$Sv/h, moderated neutrons)** | | | |
| No neutron response: gamma source | O | ND | X |
| Neutron response: neutron and gamma sources | O | ND | O |

As many neutron sensors are also sensitive to gamma radiation, neutron indications may potentially be triggered by high-intensity gamma fields. To explore this, the Mobiles were tested first with a high-intensity gamma field alone. Then, to check the functionality of the neutron sensor, a neutron source was added to the high-intensity gamma field. Mobile D performed very well in both portions of this test for the unmoderated neutron source, though it did not indicate neutrons in all trials when a gamma source was added to a moderated neutron source. A neutron indication was incorrectly produced in Mobile A when moderated neutron sources were not present in a high-intensity gamma field. Mobile C was not tested.

Radionuclide Identifications

For all radionuclide identification tests, sources were placed at three heights (Bottom, Middle, and Top of Table 49) and tested as both stationary in front of the instrument (static mode) and passing by the instrument (dynamic mode), with the parameters given in Table 49. Mobiles were tested with SNM, industrial, medical, and NORM sources, both with and without shielding. Only data from the event files were available. As was discussed previously with the alarm probability, results are significantly improved in static mode, though even in this mode the percentage of configurations (source and height) each with 10 trials with 10 correct identifications is only $\sim$ 70 %. The percentage remains at this level in dynamic mode for Mobile A but falls to between 6 % to 50 % for the other three instruments. Identification of an HEU source occurred in all trials for Mobile A in both modes (WGPu not tested). Mobile D identified both HEU and WGPu in all trials and heights in static mode but had difficulties with WGPu in dynamic mode. Mobiles B and C did not perform as well in static mode for SNM sources as A and D, and Mobile C did not achieve 10 identifications in 10 trials in any height in dynamic mode for HEU (no data on WGPu).

The instruments were also tested with shielded medical and industrial sources commonly found in commercial shipments (referred to as "shipping sources" in the standard), and the static mode in these cases also produces a higher probability of identification. Only data from the event files were available. For the shipping sources, correct identification occurred in 100 % of the trials (Mobiles B−D, Mobile A was not tested). In the dynamic mode, this percentage decreases to as low as 10 % (Mobile B) and as high as 80 % (Mobile D). Medical sources generally had a slightly lower probability of being identified in static mode than shipping sources.

The Mobiles had a difficult time identifying SNM sources when simultaneously paired with other non-SNM sources (e.g., NORM or medical sources). A correct identification in these cases required identification of both the SNM source and non-SNM source. The percentage of configurations with correct identifications observed in all trials was at most 50 % (Mobile B) and was clustered around $\sim$ 15 % for Mobiles C and D. Data from the event files were often slightly different from data observed by the operator (by up to 10 %). Data for Mobile A were not available.

**Environmental, Electromagnetic, and Mechanical Tests**

Summaries of the test results are shown in Tables 54, 55, and 56. Testing was not performed for Mobile A. None of the tests damaged the instruments. In general, they performed poorly across all tests. The only test in which positive results were observed was the electrostatic discharge test, in which neither tested Mobile alarmed at any voltage. However, there was no data reported to indicate if the readings remained within the pre-test range or if there were any identifications. For most tests, instrument readings were not noted in the reports. Radio frequencies, impact, vibrations, dust, temperature changes, and humidity changes affected correct behavior of all tested Mobiles.

Table 54: Environmental tests for the Mobiles. An "X" is used for "yes", and an "O" is used for "no". "ND" indicates that there is no data available or the instrument was not tested. No readings were recorded for any instrument. Data below was extracted only from alarms and identifications.

| | Mobile | | |
|---|---|---|---|
| | B | C | D |
| **Temperature Test (-30 °C to +55 °C)†** | | | |
| Gamma response unaffected | O | ND | O |
| Neutron response unaffected | ND | ND | ND |
| Operational temperature range for gammas (°C) | 0 to +22 | ND | +22 to +55 |
| Operational temperature range for neutrons (°C) | ND | ND | ND |
| **Humidity Test (40 % to 93 % at 40 °C)†** | | | |
| Gamma response unaffected | O | ND | O |
| Neutron response unaffected | ND | ND | ND |
| **Dust Test (IEC 60529 IP54 [35])** | | | |
| Instrument free of dust ingress that interferes with functionality | X | ND | X |
| Gamma response unaffected | O | ND | O |
| Neutron response unaffected | ND | ND | X |
| †Based on identifications only. No data on alarms or readings. | | | |

Table 55: Electromagnetic tests for the Mobiles. An "X" is used for "yes", and an "O" is used for "no". "ND" indicates that there is no data available or the instrument was not tested, and "N" indicates that the instrument worked correctly at all frequencies. "BR" is used for "broad range", when the instrument response is affected for a large number of frequencies.

| | Mobile | | |
|---|---|---|---|
| | B | C | D |
| **Electrostatic Discharge Test (up to $\pm$6 kV)** | | | |
| Gamma response unaffected | X* | ND | X* |
| Neutron response unaffected | X* | ND | X* |
| **Radio Frequency (80 MHz to 2.5 GHz at 10 V/m)** | | | |
| Gamma response unaffected | O | O | O |
| Neutron response unaffected | ND | O | O |
| Frequencies with susceptibilities | BR | ND | BR |
| **Radiated Emissions (30 to $>$ 960 MHz at 100 to 500 $\mu$V/m)** | | | |
| Emissions lower than maximum allowed | O | ND | O |
| *Based only an alarm data. No data available on readings or identifications. | | | |

Table 56: Mechanical tests for the Mobiles. An “X” is used for “yes”, and an “O” is used for “no”. Mobile C was not tested.

| | Mobile | |
|---|---|---|
| | **B** | **D** |
| **Vibration Test (ANSI/IEEE 42.43 [28])** | | |
| Instrument free of damage | ND | X |
| Response unaffected | ND | O |
| **Impact Test (1.0 J impacts)** | | |
| Instrument free of damage | X | X |
| Gamma response unaffected | O | O |
| Neutron response unaffected | ND | ND |

## 2.8 Test Results for Radiation Portal Monitors (RPMs)

Ten RPMs were tested (see Table 57), six by DNDO and four by the JRC. Eight were instrumented with neutron detectors. A complete summary of the test results for the RPMs can be found in references [14] and [15].

Table 57: System information for RPMs. Instruments were tested by DNDO, unless denoted with * for those tested by JRC. "ND" indicates that there is no data available or the instrument was not tested.

| Manufacturer/Model | Type | Gamma Sensor | Gamma Range (MeV) | Neutron Sensor |
|---|---|---|---|---|
| NucTech RM2000 | Vehicle/Double sided | Organic plastic scintillator | 0.04−3 | $^{3}$He |
| Rad Comm RC4138 | Vehicle and rail/Double sided | PVT | 0.03−2 | $^{6}$LiI |
| Thermo Scientific ASM V | Vehicle and cargo/Double sided | PVT | 0.014−3 | $^{10}$B |
| Rapiscan Systems TSA VM250 | Vehicle/Double sided | PVT | 0.04−3 | $^{10}$B |
| Rapiscan Systems TSA PM700 | Pedestrian/Double sided | PVT | 0.04−3 | $^{10}$B |
| Rapiscan Systems TSA MD134 | Mobile/Single sided | PVT | 0.04−3 | $^{6}$Li |
| Aspect Yantar 1A* | Vehicle/Double sided | Styrene-based scintillator | ND | $^{3}$He |
| Polimaster PM5000A-10H* | Vehicle/Double sided | PVT | 0.02−3 | $^{6}$LiZnS |
| Saphymo RCVL2-S7* | Vehicle/Double sided | Plastic scintillator | ND | None† |
| Symetrica Discovery Portal*‡ | Vehicle/Double sided | PVT | ND | None |
| † Capability can be added. ‡ Instrument was a prototype. | | | | |

Parameters used for testing are listed in Table 58. Three heights were used for the main alarm tests. Actual values of heights varied with RPM type. Data was taken in dynamic mode, with sources passing by at a fixed speed, dependent on RPM type, as described in the standards.

Table 58: Summary of required test parameters for the RPMs.

| Parameter | Vehicle | Pedestrian | Rail |
|---|---|---|---|
| Bottom height (m) | 0.2 | 0.1 | 0.2 |
| Middle height (m) | 2.25 | 1.0 | 3.5 |
| Top height (m) | 4.5 | 2.0 | 7.0 |
| Speed (m/s) | 2.2 | 1.2 | 2.2 |

### General Description and Requirements

A summary of the general description and requirements for RPMs is shown in Table 59. No data was collected for instruments G to J. All RPMs were equipped with occupancy sensors and most of them were able to measure the radiation from a moving object within the detection zone. The user interfaces included most of the necessary information, though the data format of only two instruments complied with the ANSI N42.42 standard [34].

Table 59: General characteristics of RPMs. An "X" is used if the system has the feature, and an "O" if it does not. "ND" indicates that there is no data available or the instrument was not tested.

| | RPM | | | | | |
|---|---|---|---|---|---|---|
| | A | B | C | D | E | F |
| Occupancy sensor | X | X | X | X | X | X |
| Measure speed | X | O | X | X | X | O |
| Functional in mixed traffic | X | O | X | X | X | O |
| Indication if object stops within detection zone | X | X | X | X | X | O |
| Statement of enclosure classification as IP54 | O | O | O | X | O | X |
| External markings permanently fixed | X | O | O | X | X | O |
| Ability to test without radiation sources | O | O | X | O | X | O |
| Ability to transfer data to external device | X | X | X | X | X | X |
| Data format as defined in the ANSI N42.42 standard | O | O | X | O | X | O |
| Wireless capabilities | O | O | O | O | O | O |
| Ability to measure a static object | X | X | X | O | X | X |
| Ability to measure a moving object | X | X | X | X | X | X |
| Mode (static/dynamic) user-selectable | O | O | O | O | X | O |
| Ability to capture photo or video | O | X | X | X | X | X |
| Access to controls limited to authorized users | X | X | X | X | X | X |
| Supervisory access to alarm selection criteria | X | X | X | O | X | X |
| Ability to operate on internal battery supply | X | X | X | X | ND | X |
| If able, ability to operate on battery for 3 hour | ND | X | O | X | ND | X |
| Documentation provided | X | X | X | X | X | X |

**Radiological Tests**

Radiological tests were performed to test instrument detection and identification response to both gamma and neutron radiation sources. The following outlines the highlights from these tests.

False Alarm Test

The false alarm rate was determined by performing at least 4500 occupancies. A summary of the false alarm results is shown in Table 60. Seven out of ten RPMs displayed a very low false gamma alarm rate, and very few false neutron alarms were triggered.

Gamma Radiation Detection Capabilities

Results are shown in Table 61. The gamma alarm function of the instruments was tested with an array of radionuclides at the three heights specified in Table 58. Three of the ten RPMs (A, C, F) alarmed in at least 59 of 60 trials for all sources at all heights. Most of the other RPMs met this metric in greater than $\sim$ 70 % of the tests. The sources that were most difficult to detect were the low-energy gamma source that is a possible indicator of WGPu and the HEU-like gamma source.

Only RPMs D and E had the ability to provide an over-range indication, and RPMs C, D, and H did not alarm or over-range during the test. Most RPMs remained in an alarm or over-range state until the removal of the source, and most returned to correct behavior after 1 minute.

Table 60: False alarm test for the RPMs. “NA” indicates “not applicable”. ‘ND” indicates that there is no data available or the instrument was not tested.

| RPM | Trials | Gamma alarms | Neutron alarms |
|---|---|---|---|
| A | 4952 | 1 | 5 |
| B | 4956 | 1 | 0 |
| C | 4954 | 0 | 0 |
| D | 4955 | 10 | 1 |
| E | ND | 10 | 1 |
| F | 5296 | 0 | 0 |
| G | 7436 | 0 | NA |
| H | 6357 | 0 | 1 |
| I | 5475 | 249 | NA |
| J | 6422 | 0 | 2 |

Neutron Radiation Detection Capabilities

Results are shown in Table 62. The neutron alarm function was tested with a moderated and unmoderated neutron source at the three heights specified in Table 58 for the eight RPMs instrumented with neutron detectors. Generally, the RPMs performed very well for the unmoderated source, with almost all alarming in at least 59 of 60 trials at the bottom and middle height. The number of RPMs reaching this level decreased to approximately half at the top height for this source. For the moderated source, half of the RPMs performed slightly beneath the level of 59 alarms in 60 trials, whereas the others did not alarm during half of the trials for any height.

As many neutron sensors are also sensitive to gamma radiation, neutron indications may potentially be triggered by high-intensity gamma fields. The RPMs were first exposed to a high-intensity gamma field alone, in which they should not trigger a neutron alarm. Then, to check the functionality of the neutron sensor, neutron sources were added to the high-intensity gamma field, and the occurrence of the neutron alarm is verified. Of the five RPMs tested, none indicated neutrons erroneously when exposed to a high-intensity, high-energy gamma field only, and all responded correctly with the addition of an unmoderated neutron source. Probability of neutron detection was slightly less for RPMs A to C when moderated neutron sources were added to the gamma field, as compared to unmoderated neutron sources.

**Environmental, Electromagnetic, and Mechanical Tests**

Summaries of the results of these tests are shown in Tables 63, 64, and 65. Testing was not performed for instruments G to J. The two RPMs tested in different environmental conditions both performed moderately well, though a few of the radiation readings deviated from their pre-test values by amounts greater than the allowed range. For the available data, the dust and moisture test presented no issues for the instruments. Neither RPM exposed to a range of radio frequencies displayed any susceptibilities. During the electrostatic discharge test, the gamma response of two of the five RPMs (B and C) were unaffected, whereas the neutron response was affected in all five instruments at various discharge voltages. The radiated field emitted from both tested RPMs (A and C) was greater than the maximum allowed at most frequency emission ranges. RPM A exhibited higher fields in more configurations than RPM C. None of the four RPMs tested for microphonic impact were damaged during testing, and the responses of three of the four remained unaffected by the impact. RPM C alarmed due to impact (gamma only).

Table 61: Gamma radiation tests for the RPMs. An "X" is used for "yes", and an "O" is used for "no". "ND" indicates that there is no data available or the instrument was not tested. Data are from the operator display only. For information recorded in event files, see Refs. [14, 15].

| | **RPM** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** |
| **Response to Gamma Radiation: HEU-like source (alarm in $\geq$ 59 of 60 trials)** | | | | | | | | | | |
| Alarm: bottom height | X | X | X | X | O | X | X | O | O | O |
| Alarm: middle height | X | X | X | X | O | X | X | O | X | O |
| Alarm: top height | X | O | X | O | ND | X | O | O | O | O |
| **Response to Gamma Radiation: WGPu-like source (alarm in $\geq$ 59 of 60 trials)** | | | | | | | | | | |
| Alarm: bottom height | X | X | X | X | X | X | X | X | X | X |
| Alarm: middle height | X | X | X | X | X | X | X | X | X | X |
| Alarm: top height | X | X | X | X | X | X | X | X | X | X |
| **Response to Gamma Radiation: low-energy source (alarm in $\geq$ 59 of 60 trials)** | | | | | | | | | | |
| Alarm: bottom height | X | X | X | O | O | X | O | O | O | O |
| Alarm: middle height | X | O | X | O | O | X | O | O | O | O |
| Alarm: top height | X | O | X | O | O | X | O | O | X | O |
| **Response to Gamma Radiation: medium-energy source (alarm in $\geq$ 59 of 60 trials)** | | | | | | | | | | |
| Alarm: bottom height | X | X | X | X | X | X | X | O | X | X |
| Alarm: middle height | X | X | X | X | X | X | X | O | O | X |
| Alarm: top height | X | X | X | X | X | X | X | O | O | X |
| **Response to Gamma Radiation: high-energy source (alarm in $\geq$ 59 of 60 trials)** | | | | | | | | | | |
| Alarm: bottom height | X | X | X | X | X | X | X | X | O | X |
| Alarm: middle height | X | X | X | X | X | X | X | X | O | X |
| Alarm: top height | X | X | X | X | X | X | X | X | X | X |
| **Response to Gamma Radiation: NORM sources (alarm in $\geq$ 59 of 60 trials)** | | | | | | | | | | |
| Alarm: bottom height | X | X | X | X | X | X | X | X | X | X |
| Alarm: middle height | X | X | X | X | X | X | X | X | X | X |
| Alarm: top height | X | X | X | X | ND | X | X | X | X | X |
| **Over-Range ($>$ maximum or 100 $\mu$Sv/h medium-energy gamma source)** | | | | | | | | | | |
| Equipped with over-range indication | O | O | O | X | X | O | ND | ND | ND | ND |
| Alarm in over-range conditions | X | X | O | O | X | X | X | O | X | X |
| Alarm remained until source removed | ND | ND | X | X | X | X | ND | ND | ND | ND |
| Returned to normal operation within 1 minute | X | X | X | X | X | X | ND | X | O | X |

Table 62: Neutron radiation tests for the RPMs. An “X” is used for ”yes”, and an “O” is used for ”no”. “ND” indicates that there is no data available or the instrument was not tested. Data are from the operator display only. For information recorded in event files, see Refs. [14, 15]. Nine trials, instead of three, were performed for the Neutron Indication in the Presence of Photons.

| | RPM | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** | **J** |
| **Response to Neutron Radiation: unmoderated source (alarm in $\geq$ 59 of 60 trials)** | | | | | | | | | | |
| Alarm: bottom height | X | X | O | X | X | X | ND | X | ND | O |
| Alarm: middle height | X | X | X | X | O | X | ND | X | ND | X |
| Alarm: top height | O | O | O | O | ND | X | ND | X | ND | X |
| **Response to Neutron Radiation: moderated source (alarm in $\geq$ 59 of 60 trials)** | | | | | | | | | | |
| Alarm: bottom height | O | O | O | X | O | X | ND | O | ND | O |
| Alarm: middle height | O | O | O | O | O | X | ND | O | ND | O |
| Alarm: top height | O | O | O | O | ND | O | ND | O | ND | O |
| **Neutron Indication in Presence of Photons (gamma high-energy source at 100 $\mu$Sv/h)** | | | | | | | | | | |
| No neutron response: high-energy gamma source | X | X | X | X | ND | X | ND | ND | ND | ND |
| Neutron response: unmoderated neutron and high-energy gamma source | X | X | X | X | ND | X | ND | ND | ND | ND |
| Neutron response: moderated neutron and high-energy gamma source | O | O | O | X | ND | X | ND | ND | ND | ND |

Table 63: Environmental tests for the RPMs. An “X” is used for ”yes”, and an “O” is used for ”no”. Pre-test and post-test refer to the instrument readings (e.g., ambient dose equivalent rate, counts per second). RPMs B, E to F were not tested upon manufacturer request or time constraints. “ND” indicates that there is no data available or the instrument was not tested.

| | **RPM** | |
|---|---|---|
| | **A** | **C** |
| **Temperature Test (-30 °C to +55 °C)** | | |
| Gamma response unaffected | O | X |
| Neutron response unaffected | X | O |
| Operational temperature range for gammas (° C) | -30 to +35 | -30 to +55 |
| Operational temperature range for neutrons (° C) | -30 to +55 | 22 to +55 |
| **Humidity Test (40 % to 93 % at 40 °C)** | | |
| Gamma response unaffected | O | X |
| Neutron response unaffected | O | O |
| **Dust Test (IEC 60529 IP54 [35])** | | |
| Instrument free of dust ingress that interferes with functionality | ND | X |
| Gamma response unaffected | ND | X |
| Neutron response unaffected | ND | X |
| **Moisture Test (IEC 60529 IP54 [35])** | | |
| Instrument free of water ingress that interferes with functionality | X | X |
| Gamma response unaffected | X | X |
| Neutron response unaffected | X | X |

Table 64: Electromagnetic tests for the RPMs. An "X" is used for "yes", and an "O" is used for "no". "ND" indicates that there is no data available or the instrument was not tested, and "N" indicates that the instrument worked correctly at all frequencies.

| | RPM | | | | | |
|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** |
| **Electrostatic Discharge Test (up to ±6 kV)** | | | | | | |
| Gamma response unaffected | O | X | X | O | ND | O |
| Neutron response unaffected | O | O | O | O | ND | O |
| **Radio Frequency (80 MHz to 2.5 GHz at 10 V/m)** | | | | | | |
| Gamma response unaffected | X | ND | X | ND | ND | ND |
| Neutron response unaffected | X | ND | X | ND | ND | ND |
| Frequencies with susceptibilities | N | ND | N | ND | ND | ND |
| **Radiated Emissions (30 to $>$ 960 MHz at 100 to 500 $\mu$V/m)** | | | | | | |
| Emissions lower than maximum allowed | O | ND | O | ND | ND | ND |
| **Conducted Distrubances Induced by Bursts and Radio Frequencies** | | | | | | |
| Gamma response unaffected | X$^\dagger$ | ND | O | ND | ND | ND |
| Neutron response unaffected | X$^\dagger$ | ND | O | ND | ND | ND |
| **Surges and Oscillatory Waves (up to 2kV)** | | | | | | |
| Gamma response unaffected | ND | X | X | X | ND | X |
| Neutron response unaffected | O | O | X | X | ND | X |
| $^\dagger$Test only performed without occupancies. | | | | | | |

Table 65: Mechanical tests for the RPMs. An "X" is used for "yes", and an "O" is used for "no".

| | RPM | | | |
|---|---|---|---|---|
| | **A** | **C** | **D** | **F** |
| **Impact Test (1.0 J impacts)** | | | | |
| Instrument free of damage | X | X | X | X |
| Gamma response unaffected | X | O | X | X |
| Neutron response unaffected | X | X | X | X |

## 2.9 Test Results for Spectroscopic Radiation Portal Monitors (SRPMs)

A total of seven SRPMs were tested (see Table 66), four by DNDO and three by the JRC. A complete description of the test results for the SRPMs can be found in Refs. [16, 17]. All but one of the SRPMs were equipped with neutron detectors. Environmental, electromagnetic, and mechanical tests were not performed for this instrument class. One SRPM was a prototype, and its results are not included in this report.

Table 66: System Information for SRPMs. Instruments were tested by DNDO, unless denoted with * for those tested by JRC.

| Manufacturer/Model | Type | Gamma Sensor | Gamma Range (MeV) | Neutron Sensor |
|---|---|---|---|---|
| Ortec Detective-SPM-16 | Vehicle/Double sided | HPGe | 0.04−8 | $^6$LiI |
| Totem Plus Radioactive Material Detector System | Vehicle/Double sided | NaI(Tl) | 0.025−3 | $^3$He |
| Raytheon ASP | Vehicle/Double sided | NaI(Tl) | 0.02−10 | $^3$He |
| NucTech RM1000NH | Pedestrian/Double sided | NaI(Tl) | 0.025−3 | $^3$He |
| Mirion Spir Ident GN* | Pedestrian/Single sided | NaI(Tl) / GM tube | 0.025−3 | $^3$He |
| Mirion Spir Ident Mobile G2L* | Mobile† / Single sided | NaI(Tl) | 0.025−3 | None |
| Symetrica Crystal Portal* | Vehicle/Double sided | NaI | 0.025−3 | $^6$Li:ZnS(Ag) |
| Note: dash indicates information not provided. † Tested as a pedestrian portal. | | | | |

Parameters used for testing are listed in Table 67. Three heights were used for the main detection and identification tests. Actual values of heights varied with SRPM type. Data was taken in both static mode, with sources stationary in front of the instruments, and dynamic mode, with sources passing by at a fixed speed, also dependent on SRPM type.

Table 67: Summary of Nominal Test Parameters for the SRPMs.

| Parameter | SRPM | | |
|---|---|---|---|
| | A, B, C | D | F, G |
| Type (tested as) | Vehicle | Pedestrian | Pedestrian |
| Bottom height (m) | 0.2 | 0.25 | 0.1 |
| Middle height (m) | 2.25 | 1.125 | 0.95 |
| Top height (m) | 4.5 | 2.0 | 2.0 |
| Speed (m/s) | 2.2 | 1.2 | 1.2 |
| Static dwell time (s) | 30 | 30 | 30 |

### General Description and Requirements

A summary of the general description and requirements for SRPMs is shown in Table 68. In addition, the SRPMs provide visual indications for neutron alarm, gamma alarm, radionuclide identified, radionuclide category, occupancy sensor status, system failure, system condition, operating mode, background change, occupancy sensor failure, loss of main power, detector failure, and communication failure. There were no uniform alarm indication and radionuclide identifications displays for the SRPMs, as each model had its own set of alarm colors and user interface displays. The installation and operation manuals provided by the manufacturers did not include all necessary information required by the standards, although the information provided would likely allow a user to operate the instrument.

Table 68: General Characteristics of SRPMs. An “X” is used if the system has the feature, and an “O” if it does not. “ND” indicates that there is no data available or the instrument was not tested.

| | SRPM | | | | | |
|---|---|---|---|---|---|---|
| | A | B | C | D | F | G |
| Occupancy sensor | X | X | X | X | X* | X* |
| Speed sensor | X | X | X | O | X† | X† |
| Measure speed | X | X | X | O | X | X |
| Functional in mixed traffic | X | X | X | O | ND | ND |
| Functional bi-directionally | O | X | X | X | X | X |
| Indication if object stops within detection zone | O | X | X | X | ND | ND |
| Statement of enclosure classification as IP54 | O | O | O | X | X | X |
| External markings of manufacturer, instrument name | X | X | X | X | X | X |
| External markings permanently fixed | X | X | X | X | X | X |
| Access to controls limited to authorized users | X | X | X | X | X | X |
| Ability to test without radiation sources | O | X | X | X | O | O |
| Ability to transfer data to external device | X | X | X | X | X | X |
| Data format as defined in the ANSI N42.42 standard | X | X | X | X | O | O |
| Wireless capabilities | O | O | O | O | O | O |
| Transfer protocol described in manuals | O | X | X | O | X | X |
| Ability to indicate identification of unknown peak | O | O | X | O | X | X |
| Confidence indication reported | X | O | X | X | X | X |
| If reported, confidence indication described in manual | X | - | X | X | X | X |
| Ability to measure a static or moving object | X | X | X | X | X | X |
| Mode (static/dynamic) user-selectable | X | X | X | X | X | X |
| Ability to capture photo or video | X | X | O | O | X | X |
| Supervisory access to alarm selection criteria | X | X | O | O | X | X |
| Supervisory access to energy calibration information | O | X | X | X | X | X |
| Supervisory access to efficiency information | O | X | O | O | X | X |
| Ability to operate on internal battery supply | O | O | O | O | X | X |
| If able ability to operate on battery for 3 hour | - | - | - | - | X‡ | X‡ |
| Documentation provided | X | X | X | X | X | X |

* Units under test not equipped with occupancy sensors. † Sensors not used. ‡ Information from manual.

## Radiological Tests

Radiological tests were performed to test instrument alarm and identification response to both gamma and neutron radiation sources, as well as identification abilities. The following outlines the highlights from these tests.

### False Alarm Test

The false alarm rate was determined by performing a total of at least 5000 occupancies for the five portals with occupancy sensors and observing the SRPMs for 10 hours of testing for the two portals without these sensors. A summary of the results is shown in Table 69, which illustrates a fairly low number of false alarms across most of the SRPMs. The types of non-background radiation identifications were high-energy gamma (SRPM A) and neutrons (SRPM G). It is possible for SRPMs to alarm without also issuing an identification (e.g., the alarms observed in SRPM D). In the case of SRPM B, all gamma alarms were accompanied by identifications of NORM radionuclides. SRPM A is programmed to alarm only for SNM, depleted uranium, and americium-241.

Table 69: False Alarm Test for the SRPMs

| SRPM | Trials/duration | Gamma alarms | Neutron alarms | Non-background IDs |
|---|---|---|---|---|
| A | 5725 | 0 | 0 | 1 |
| B | 5558 | 27 | 0 | 0 |
| C | 6215 | 0 | 11 | 0 |
| D | 5789 | 3 | 3 | 0 |
| F | 10 h | 0 | 0 | 0 |
| G | 10 h | 0 | 1 | 1 |

Gamma Radiation Detection Capabilities

Results are shown in Table 70. The gamma alarm indication was tested using an HEU-like source and a WGPu-like source with parameters given in Table 67 for a moving source.

Table 70: Gamma Radiation Tests for the SRPMs. An "X" is used for "yes", and an "O" is used for "no". "ND" indicates that there is no data available or the instrument was not tested. Data are from the operator display only. For information recorded in event files, see Refs. [16, 17].

| | SRPM | | | | | |
|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **F** | **G** |
| **Response to Gamma Radiation: HEU-like source (alarm in $\geq$ 59 of 60 trials)** | | | | | | |
| Alarm: bottom height | O* | O | O | O | O | O |
| Alarm: middle height | O* | O | O | O | O | X |
| Alarm: top height | O* | O | O | O | O | O |
| **Response to Gamma Radiation: WGPu-like source (alarm in $\geq$ 59 of 60 trials)** | | | | | | |
| Alarm: bottom height | O* | O | O | X | O† | O† |
| Alarm: middle height | O* | O | O | X | O† | X† |
| Alarm: top height | O* | O | O | X | O† | O† |
| **Over-Range (> maximum or 100 $\mu$Sv/h medium-energy gamma source)** | | | | | | |
| Equipped with over-range indication | O | O | O | O | O | O |
| Alarm in over-range conditions | X | X | X | X | X | X |
| Alarm remained until source removed | X | O | O | X | ND | ND |
| Returned to normal operation within 1 minute | X | X | X | X | X | X |

* Instrument only alarms to neutrons and SNM sources.
† Source strength approximately 4.5 times higher than used to test other instruments.

Different source strengths for the WGPu-like source were used by the JRC and DNDO due to availability of sources. Generally, the SRPMs tested with the lower strength WGPu-like source had difficulties detecting the source, while those tested with the stronger source detected more consistently at most heights (triggering at least 59 alarms out of 60 trials still proved troublesome). SRPM D was able to alarm in at least 59 out of 60 trials for all heights for this source. For the HEU-like source, alarms were triggered consistently by

SRPMs B, C, F, and G (middle height only), and D (all heights), though most still did not all alarm in 59 out of 60 trials. SRPM A did not alarm except to indicate sources of interest such as HEU, WPGu, depleted uranium, and americium-241. However, without alarming, it correctly identified the HEU-like source at all heights and often identified the WGPu-like source.

Over-range indications alert users to potentially high radiation fields. This threshold could be the point at which an instrument's efficiency decreases rapidly, where its reading becomes saturated and unreliable, or where user safety may become an issue. No SRPM provided a specific over-range indication. Instead, some instruments displayed indications such as "High Dose" or "Fault", which could indicate over-range conditions or other situations. To test their behavior while exposed to a high-strength source, the SRPMs did alarm in all trials, though not all displayed accurate identifications and not all remained in alarm for the test duration. After exposure to this high-strength source, all systems were able to recover, detecting a low-activity source in all trials.

Neutron Radiation Detection Capabilities

Results are shown in Table 71. For the six SRPMs equipped with neutron detectors, the neutron alarm indication was tested using both unmoderated and moderated neutron sources. SRPMs A to D and G detected the unmoderated neutron source consistently at the bottom and middle heights (detection probability was slightly less at the top height).

Table 71: Neutron Radiation Tests for the SRPMs. An "X" is used for "yes", and an "O" is used for "no". "ND" indicates that there is no data available or the instrument was not tested. Data are from the operator display only, unless otherwise indicated. For information recorded in event files, see Refs. [16, 17].

| | SRPM | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | G |
| **Response to Neutron Radiation: unmoderated source (alarm in $\geq$ 59 of 60 trials)** | | | | | |
| Alarm: bottom height | X$^{\dagger}$ | X | X | X | X* |
| Alarm: middle height | X$^{\dagger}$ | X | X | X | X* |
| Alarm: top height | X$^{\dagger}$ | O | O | O | O* |
| **Response to Neutron Radiation: moderated source (alarm in $\geq$ 59 of 60 trials)** | | | | | |
| Alarm: bottom height | X$^{\dagger}$ | O | O | O | O* |
| Alarm: middle height | X$^{\dagger}$ | O | O | O | ND |
| Alarm: top height | X$^{\dagger}$ | O | O | O | ND |
| **Neutron Indication in Presence of Photons** (gamma high-energy source at 100 $\mu$Sv/h)** | | | | | |
| No neutron response: high-energy gamma source | O$^{\ddagger}$ | X | O | X | ND |
| Neutron response: neutron and high-energy gamma sources | X$^{\ddagger}$ | X | X | O | ND |

$^{\dagger}$ Alarms in 10 out of 10 trials.
* From event files, as operator data was not available.
** Above results were identical using both unmoderated and moderated neutron sources
$^{\ddagger}$ Instrument cannot distinguish between neutron and high-intensity gamma sources.

For the moderated neutron source, the detectability was reduced by half compared to the unmoderated source at all heights for SRPMs B to D. SRPM A did alarm in all trials for this source, but only 10 trials were performed. Although the alarm probability was nearly 100 % for the SRPM E in the operator display, the probability was reduced to $\sim$ 30 % in the event file.

As many neutron sensors are also sensitive to gamma radiation, neutron indications may potentially be triggered by high-intensity gamma fields. To explore this, the SRPMs were tested first with a high-intensity gamma field alone. Then, to check the functionality of the neutron sensor, a neutron source was added to the high-intensity, high-energy gamma field (both moderated and unmoderated), and the absence of the neutron alarm was verified. A neutron indication was incorrectly produced in SRPM C when neutron sources were not present in the gamma field. For the two SRPMs that did not display a neutron indication without a neutron source (B and D), only SRPM B provided a neutron indication in all trials when a neutron source was presented together with the gamma source, exhibiting proper behavior. SRPM A did not distinguish between neutrons and high-intensity gamma sources.

SRPM G was tested with a medium-energy gamma source and unmoderated neutrons only. SRPM G performed correctly in both portions of the test.

Radionuclide Identifications

For all radionuclide identification tests, sources were placed at three heights and tested as both stationary in front of the instrument (static mode) and passing by the instrument (dynamic mode), with the parameters given in Table 67. Separately and without shielding, SRPMs were tested with SNM, industrial, medical, and NORM sources. In general, the SRPMs accurately identified industrial and NORM sources but had difficulties identifying medical sources and depleted uranium. Probability of identification usually increased in static mode compared to the dynamic mode, although additional radionuclides are falsely identified by some instruments.

For SNM sources, performance improved in static mode. All SRPMs, except C and D, identified both HEU and WGPu in every trial in static mode, although additional radionuclides that were not part of the source were also identified in some trials for SRPMs A (top height) and G (all heights) for the WGPu source. In this mode, SRPM D rarely identified WGPu, and SRPM C did not identify that source in its event file but did display the identification to operator display, along with additional radionuclides. Performance generally degraded slightly in dynamic mode, with difficulties encountered with the HEU source more than with the WGPu source (SRPMs F and G). SRPMs C and D continued to display incorrect identifications for WGPu. SRPMs A and B exhibited correct identifications of both sources in almost all trials.

For shielded industrial sources, SRPMs were tested with industrial and WGPu-like sources. Most SRPMs consistently identified the sources, although difficulties were observed with an industrial source for SRPMs D to G in dynamic mode. Performance was enhanced in static mode, though SRPM C consistently identified additional radionuclides that were not part of the source. SRPM D had difficulties detecting the WGPu-like source for most trials. For shielded medical sources, SRPMs F and G consistently identified most sources in both static and dynamic mode. SRPMs A and B had problems identifying three of four medical sources in dynamic mode (one was consistently identified correctly but along with other radionuclides). SRPM C rarely identified any source correctly in this mode. $^{67}$Ga was frequently identified as HEU. SRPM D was not tested with most sources because the instrument needed to be returned to the manufacturer.

To test SRPM performance when exposed to multiple sources, three instruments were tested with medical and SNM sources simultaneously. Most SRPMs had problems identifying WGPu with a medical source (though only in dynamic mode for SRPM A). SRPM A had no issues identifying both the medical source and HEU in either mode, and SRPM C consistently identified additional radionuclides that were not part of the source. SRPM B did not correctly identify HEU and the medical source in any trial for either mode at any height.

The SRPMs were also tested with different combinations of SNM together with medical sources and NORM, in order to determine the response when the emission rate of one source was much lower than the other. All SRPMs had issues identifying WGPu with either a medical or NORM source in dynamic mode and to a lesser extent HEU with either a medical or NORM source. SRPMs A and B had no difficulties with HEU and the NORM source in either mode. Some of the SRPMs identified additional radionuclides not present in the source.

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# Appendices

## A References


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[3] U.S. Department of Homeland Security Domestic Nuclear Detection Office, "ITRAP+10 Vendor Report: FLIR nanoRaider," 200-ITRAP-116228V0.00; "ITRAP+10 Vendor Report: Mirion PDS-100GN/ID," 200-ITRAP-116229V0.00; "ITRAP+10 Vendor Report: Polimaster PM1704GN," 200-ITRAP-116225V0.00; "ITRAP+10 Vendor Report: Polimaster PM1704M," 200-ITRAP-116226V0.00; "ITRAP+10 Vendor Report: RadComm MSpec," 200-ITRAP-116227V0.00.

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ITRAP-116295V0.00; "ITRAP+10 Vendor Report Polimaster PM1410," 200-ITRAP-116296V0.00; "ITRAP+10 Vendor Report Smiths Detection RadSeeker CL," 200-ITRAP-116297V0.00; "ITRAP+10 Vendor Report Smiths Detection RadSeeker CS," 200-ITRAP-116298V0.00; "ITRAP+10 Vendor Report ICx Radiation Raider," 200-ITRAP-116299V0.00.

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# B Glossary

## B.1 Definitions

A complete set of definitions for the ITRAP+10 Test Campaign may be found in ITRAP+10 Test Lexicon [36].

## B.2 Acronyms

**-A-**

| | |
|---|---|
| AC | alternating current |
| ANL | Argonne National Laboratory |
| ANSI | American National Standards Institute |

**-B-**

| | |
|---|---|
| BRD | backpack-type radiation detector |

**-C-**

| | |
|---|---|
| CORE | Common Operating and Response Environment |
| cps | counts per second |
| CZT | cadmium zinc telluride |

**-D-**

| | |
|---|---|
| DC | direct current |
| DHS | U.S. Department of Homeland Security |
| DLS | driven linear system |
| DNDO | Domestic Nuclear Detection Office |
| DU | depleted uranium |

**-E-**

**-F-**

| | |
|---|---|
| ft | feet |
| FWHM | full-width half-maximum |

**-G-**

| | |
|---|---|
| G | Gauss (unit of magnetic field, 10 G = 1 mT) |
| GADRAS | Gamma Detector Response and Analysis Software |
| GM | Geiger–Müller |
| GPS | global positioning system |
| GSD | gamma search detector |

**-H-**

| | |
|---|---|
| HDPE | high-density polyethylene |

| | |
|---|---|
| HEU | highly enriched uranium |
| HPGe | high-purity germanium |
| Hz | Hertz |

**-I-**

| | |
|---|---|
| IAEA | International Atomic Energy Agency |
| ID | identification |
| IEC | International Electrotechnical Commission |
| IEEE | Institute of Electrical and Electronics Engineers |
| IP | ingress protection |
| ITRAP+10 | Illicit Trafficking Radiation Program+10 |

**-J-**

| | |
|---|---|
| JHU/APL | Johns Hopkins University/Applied Physics Laboratory |
| JRC | Joint Research Centre |

**-K-**

| | |
|---|---|
| KCl | potassium chloride |

**-L-**

| | |
|---|---|
| LaBr | lanthanum bromide |
| LCD | liquid crystal display |
| LED | light emitting diode |
| LiI | lithium iodide |
| LLNL | Lawrence Livermore National Laboratory |

**-M-**

| | |
|---|---|
| MDA | minimum detectable activity |
| mph | miles per hour |

**-N-**

| | |
|---|---|
| NaI | sodium iodide |
| NIST | National Institute of Standards and Technology |
| NORM | naturally occurring radioactive material |
| NSD | neutron search detector |

**-O-**

| | |
|---|---|
| ORNL | Oak Ridge National Laboratory |

**-P-**

| | |
|---|---|
| PC | personal computer |
| PMMA | polymethyl methacrylate |
| PNNL | Pacific Northwest National Laboratory |
| POE | point of entry |
| PRD | personal radiation detector |

**-Q-**

| | |
|---|---|
| QA | quality assurance |
| QC | quality control |

**-R-**

| | |
|---|---|
| RF | radio frequency |
| RGPu | reactor-grade plutonium |
| RID | radionuclide identification device |
| RPM | radiation portal monitor |

**-S-**

| | |
|---|---|
| SNM | special nuclear material |
| SPRD | spectroscopic personal radiation detector |
| SRNL | Savannah River National Laboratory |
| SRPM | spectroscopic radiation portal monitor |

**-T-**

**-U-**

| | |
|---|---|
| U.S. | United States |
| USB | universal serial bus |

**-V-**

| | |
|---|---|
| V | Volts |
| V&V | verification and validation |

**-W-**

| | |
|---|---|
| WGPu | weapons-grade plutonium |

**-X-**

**-Y-**

**-Z-**

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# C List of Manufacturers

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ICX was acquired by FLIR Detection, Inc.

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JRC102016

EUR Number: 27958

PDF ISBN 978-92-79-58986-7 ISSN 1831-9424 doi:10.2788/895995

Print ISBN 978-92-79-58985-0 ISSN 1018-5593 doi:10.2788/163199

Catalogue Number: LB-NA-27958-EN-N (online)

Catalogue Number: LB-NA-27958-EN-C (print)

Luxembourg: Publications Office of the European Union, 2016

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doi:10.2788/895995

ISBN 978-92-79-58986-7