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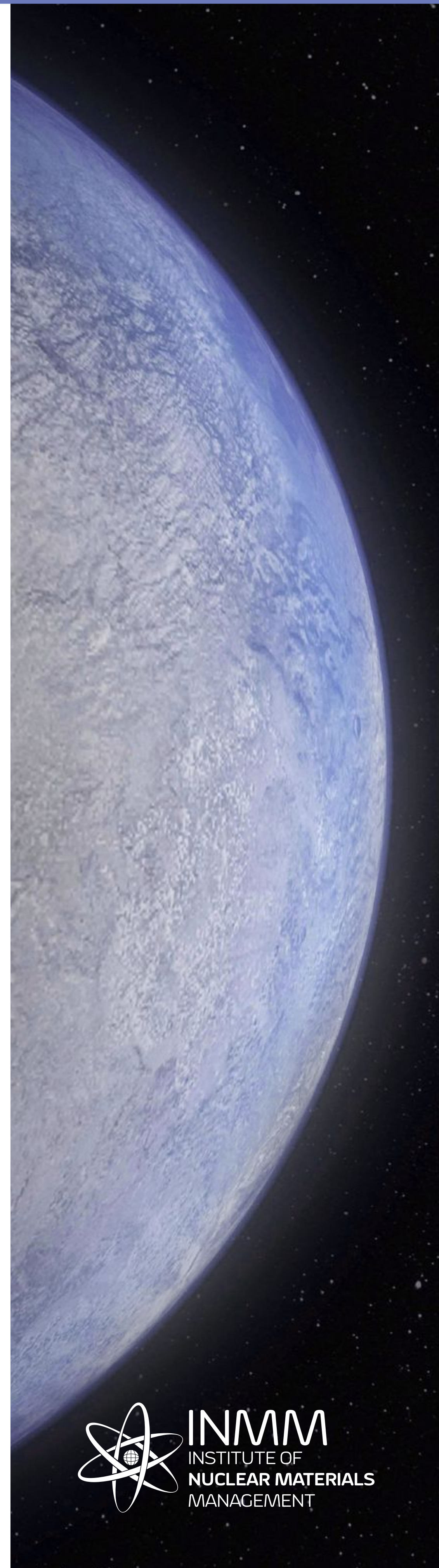

Operational Guidelines for Use of Radiation Portal Monitors in Nuclear Facilities

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Abstract

This article provides guidelines (not requirements) for the testing, operation, and maintenance of radiation portal monitors used to scan pedestrian and vehicular traffic entering or exiting nuclear facilities to prevent unauthorized removal of nuclear material. The intended audience is facility managers, supervisors, and operators who are responsible for establishing and maintaining radiation detection systems, who are likely well acquainted with physical security procedures, but may not have a familiarity with the operation of radiation detection.

KEYWORDS
radiation portal monitor, security, detection

Introduction

A radiation portal monitor (RPM) is used to automatically scan for the presence of nuclear or other radioactive material in different types of conveyances (people, vehicles, baggage, and in some cases rail cars). RPMs typically compare the radiation levels measured during an occupancy with the radiation level collected while the RPM is unoccupied. In this work, *background* will refer to the signal measured by an RPM while not occupied. If the measured radiation during an occupancy exceeds a threshold, an alarm is produced, and operators are expected to interdict the occupant and conduct further investigations to determine the source of the radiation. The alarm may be produced locally via a series of sounds and flashing lights, it may be sent to a central alarm station (CAS) for recording and further analysis, or both. Some installations may intentionally avoid alerting the occupant that an alarm has occurred.

Radiation Sources

Low levels of ionizing radiation from the environment are continuously present (i.e., background radiation). RPMs typically focus on detection of gamma radiation and neutron radiation above the naturally occurring background levels.

- Gamma radiation comes from high-energy photons emitted during the radioactive decay process; it can pass through the human body, but it is absorbed by denser materials (e.g., thick concrete, iron, lead).
- Neutron radiation occurs when neutrons are ejected from the nucleus; it can pass through metallic materials, but it is absorbed by materials with lots of hydrogen atoms (e.g., paraffin wax, plastics, water).

See Figure 1 for radiation attenuation.

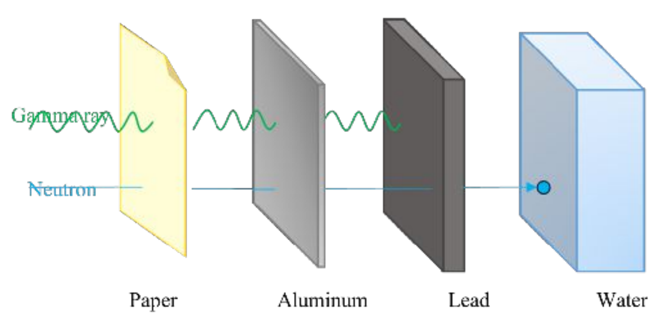

Figure 1. Radiation attenuation.

The most sensitive nuclear material, on which a nuclear facility should be secured against unauthorized removal, is defined by Section 4 of International Atomic Energy Agency's (IAEA's) Nuclear Security Series No. 13[1] as plutonium, ^{233}U, or uranium enriched in the isotopes ^{233}U or ^{235}U1. Uranium is primarily a gamma emitter, and plutonium is a gamma emitter and neutron emitter. In addition to nuclear material encountered in nuclear facilities, one should be aware that other sources of ionizing radiation are also common:

- **Medical sources:** Radiation has many uses in medicine (e.g., radioactive elements used to diagnose and treat diseases).
- **Industrial sources:** Radiation has a variety of industrial uses (e.g., radiographic weld inspection devices, density gauges) for industrial purposes. It is also present in smoke detectors and some building exit signs.
- **Naturally Occurring Radioactive Material (NORM):** Traces of uranium, potassium, or thorium, as well as their decay products, are found in many materials in goods such as ceramics, some fertilizers, and granite.

RPM Operation

The elements of all RPMs are essentially the same. A radiation detector responds to ionizing radiation and sends electrical signal pulses to electronic circuits.

See Figure 2 for elements of an RPM.

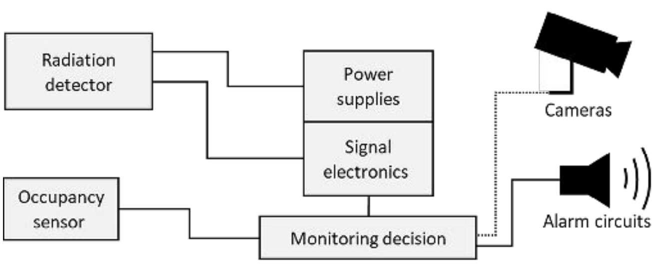

Figure 2. The elements of an RPM are a detector, the signal-conditioning electronics, an occupancy sensor, a transient signal detection circuit, and a communication device. A surveillance camera may be added.

The signals from the electronics are interpreted by the monitor's detection electronics, and a radiation level (count rate) is calculated. Generally, the count rate when the monitor is unoccupied is compared to the count rate when the monitor is occupied. The acquisition process is described in Figure 3. The alarm should also be reported at the central alarm station.

The alarm threshold is periodically updated based on the background. Background times are usually 20 to 120 seconds. During an occupancy, the count rate is frequently measured and compared with the alarm threshold. Figure 4 shows the background suppression caused by the presence of a vehicle: the engine and vehicle body block gamma rays, resulting in a reduction in the RPM count rate. This effect is more acute for vehicle RPMs (a 15%–30% reduction) than pedestrian RPMs. An alarm is generated when the measured count rate is above the alarm threshold.

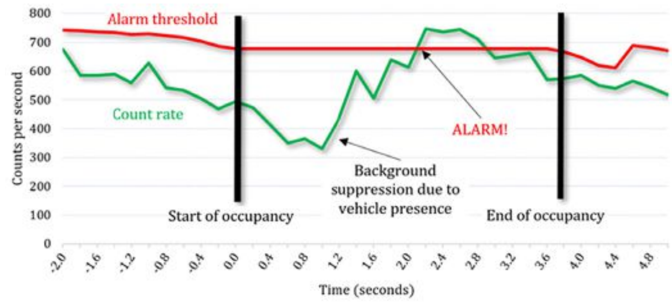

Figure 3. RPM measurement and alarm process.

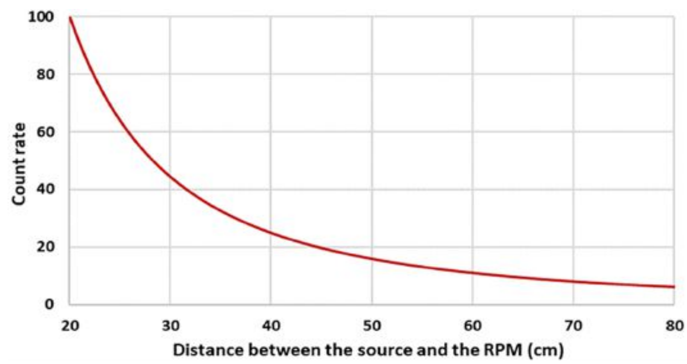

Figure 4. Impact of the distance on the count rate of an RPM.

The *1997 Update to the Application Guide for Vehicle SNM Monitors*[2] provides more detail on algorithm operation.

Setting RPM Thresholds

The alarm threshold is a compromise between sensitivity* and false alarm rate. If the alarm threshold is low, the RPM will detect a small quantity of threat material, but it is more likely to generate a false alarm because of the natural fluctuation of the background. However, if the alarm threshold is high, the RPM cannot detect small quantities of threat material, but it is less likely to cause false alarms caused by natural fluctuations in the background. To set the alarm threshold, the operator must answer the following questions:

- What quantity of threat material must be detected? "As low as possible" is not acceptable because if the RPM is too sensitive, false alarms resulting from background fluctuations can occur.
- What false alarm rate is acceptable? False alarms—if frequent—can decrease operator confidence in the

*The sensitivity corresponds to the ability of the RPM to detect a given quantity of threat material with a given probability. The objective is to detect the smallest quantity of threat material with the highest probability reasonably achievable.

operation of the RPM. However, statistically, the false alarm rate cannot be zero.

- What background levels are expected? Most monitors have high and low count rate thresholds for background to detect unexpected variation. For example, if a detector were to fail and create an abnormally high or low (zero) count rate, this would cause the RPM to enter a fault state.

A common alarm threshold method is: $AL = BKG + n\sqrt{BKG}$, where BKG is the background count rate, and n is a parameter defined by the operator (see Section 6 below).

The surveillance of the monitoring area (by a physically present guard or television surveillance) is necessary to ensure that the area around the RPM remains clear and that nothing could contaminate the natural radiation background measured by the RPM.

Detector Types for RPMs

Different detector materials can be used for different purposes. Some of the most popular ones are described here to provide a brief overview of the trade-offs of the different materials.

Gamma Detection

Most RPMs use scintillation detectors because of their low cost and large area. High purity germanium detectors may also be used for vehicle RPMs, although they are very expensive. The advantages and disadvantages of the most common gamma detectors used in RPMs are described in the Table 1.

These detectors must be protected from excessive mechanical shock and vibration. Scintillators must also be protected against direct sources of light including direct sunlight.

Neutron Detection

Few forms of nuclear material are intense neutrons emitters; neutron emitting sources are rare in the stream of commerce. Although neutron detectors can be expensive, neutron radiation is very penetrating and thus is practical for scanning vehicles for the potential presence of neutron-emitting sources.

Helium-3, or **^{3}He**. It is the most common type of neutron detection material. It is rugged, dependable, low maintenance, and has good sensitivity. In the early 2010s, a global ^{3}He shortage made ^{3}He-based neutron detection almost prohibitively

Table 1. Comparison of various gamma detectors used in vehicle RPMs

	Plastic scintillator	NaI scintillator	High-purity germanium
Advantages	Plastic scintillators are relatively cheap and rugged and can be formed into large rectangles to provide a large detector area.	NaI is the most common detector material for spectroscopic purposes because it is relatively affordable (although more expensive than plastic) and available in sizes up to 10 cm wide × 10 cm thick × 40 cm long.	High-purity germanium is the gold standard for identification; the sharp peaks make identification simple and conclusive.
Disadvantages	Plastic scintillators have poor energy resolution, which requires advanced algorithms to distinguish uranium from plutonium from other sources.	The algorithm that identifies radioactive materials must be tested for accuracy because operators will be trusting the results of the identification algorithm to allow an occupancy to proceed. Additionally, the need for a proper calibration is more acute with a spectroscopic system.	This is the most expensive detector material. Crystals can cost $100,000 each, and four to eight crystals are required to scan a large vehicle. High-purity germanium must be kept at very cold temperatures (−200°C), which require constant electricity and can be prone to failure.
Comments	Plastic is a good choice when the RPM occupancies are not expected to have many sources of NORM. Most nuclear facilities rarely see these types of NORM-bearing commodities entering or exiting the facility.	NaI is commonly used in handheld radiation detectors, often to help resolve alarms generated by plastic-based RPMs. A NaI-based RPM is useful in a stream of commerce in which there is a high distribution of NORM cargo, and the time or cost of resolving RPM alarms using handheld means would be prohibitive.	This is required for very complicated spectra such as mixed waste.

expensive; however, since that time, ^{3}He has become more available, and prices have dropped.

Four ^{3}He tubes, each 5 cm in diameter and 91 cm length, pressurized to 2 atm, provide sufficient sensitivity for most vehicle RPM applications; however, the owner must determine what neutron sensitivity is required for their facility.

Lithium. Lithium–zinc–sulfide and other lithium-based detection systems were developed in response to the aforementioned ^{3}He shortage and now provide a cost competitive alternative to ^{3}He-based systems. Lithium-6 has a relatively large cross section for neutron absorption and can be placed in other materials (glass, fibers, sheets) that take advantage of its neutron-absorbing capabilities to provide indications of a detection. Some forms come in sheets or slabs, and others come as drop-in replacements for ^{3}He tubes.

Note on the Use of Different Detectors

Uranium is primarily a gamma emitter, and plutonium is both a gamma emitter and neutron emitter. After careful consideration, a facility could select only gamma detection if only uranium is processed; similarly, a facility could select only neutron detection if only plutonium is processed at the facility. Such a decision should only be made with the consultation of experts and the explicit understanding of what the resultant minimum detectable quantity would be. Experts can also be consulted to examine secondary emissions or other effects, such as neutron emissions from some uranium compounds like UF6.

Performance Considerations

Environmental factors will significantly affect the performance of an RPM; facility owners need to be aware of these to ensure the actual RPM performance meets or exceeds the requirements. These parameters must be specified when determining the required sensitivity of an RPM.

Background

Detecting a weak radioactive source in a high-radiation background environment is analogous to hearing a quiet voice in a noisy room. The quieter the room (i.e., lower background), the easier it is to detect quiet sounds (i.e., weak radioactive sources). The natural radiation background comes from cosmic and terrestrial radiation. This background at a site should be measured before system specification. Where possible, low-background concrete should be selected—the provenance of the aggregate determines the radioactivity level in the concrete. Other radioactive sources should not be stored near the RPMs, even temporarily.

Speed

Vehicles and pedestrians should be as slow as practical during transit, giving the RPM a longer time to detect radiation from a potential source. Most vehicle RPMs are designed with a passthrough speed of 8 or 10 km/h. Slower is even better. Monitoring performance can be improved by also analyzing the second before an occupancy begins and for a second after the occupancy ends.

Pedestrians often try to crowd the area near an RPM to pass through the control area quickly; this must be avoided as it can create uncertainty around who generated the alarm. The passage should be designed to naturally slow down people and ensure each person passes through the RPM individually, such as at an ID check station or just after a turnstile.

Spacing

The distance between the pillars directly affects the overall sensitivity of the RPM (Figure 4). The pillars should be spaced as closely as safety allows for the widest anticipated vehicles.

Hence, pedestrians and vehicles should pass as close as possible to the RPMs, to maximize the signal reaching the detector and improve the detection sensitivity. For this reason, two pillars should be used (one on each side of the passage) and be spaced as closely as possible, yet still allow the widest anticipated vehicles. For vehicles, the detectors should be set up to scan the entire height of the vehicles that are expected to pass through. Using a vehicle RPM (with ~4 meter spacing) to scan pedestrians walking through is unlikely to provide adequate sensitivity; pedestrians should have their own, dedicated RPM.

Shielding

The presence of material, including the human body or the vehicle itself, between the source and the detector will reduce the ability of the RPM to detect radiation. In addition, many objects can be used to shield radioactive material: metallic canisters, lead aprons, etc. This must be accounted for in the design of the RPM and in managing the expectations of operators. Other measures to inspect for the presence of large amounts of shielding may need to be part of the overall inspection regime.

Having a pillar on each side of the pedestrian passage, as described before, helps to reduce the human-body shielding effect.

A representative vehicle should be selected for test and evaluation purposes, and a conservative test location should be selected for both vehicle and pedestrian RPMs, as shown in Figure 5.

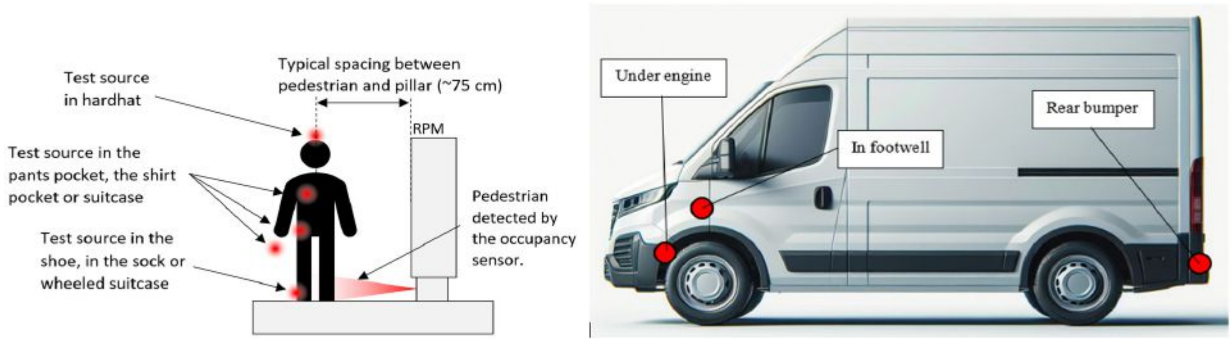

Figure 5. Sample test locations: the worst-case (but still credible) location based on testing should be used.

Source Intensity

The number of gammas emitted by a source is strongly dependent on the material type and source configuration and must be specified in the sensitivity requirements. Many materials are self-shielding. Because of the density and high atomic number of the source, gamma particles emitted from the center of the source are absorbed by the material before they can pass through the source. The amount of self-shielding depends on the density of the material (e.g., sintered uranium oxide vs. loose powder, uranium metal vs. uranium oxide) and the enrichment (e.g., uranium enriched to 5% ^{235}U or 90% ^{235}U). A sphere has the smallest surface area for a given volume and is thus a conservative geometry to assume when defining a source.

False Alarm Rate

When determining sensitivity, the false alarm rate must also be specified. A system with high sensitivity could also have a high false alarm rate, which would quickly become a nuisance to operators and reduce overall system effectiveness. Owing to the background suppression from the presence of vehicles, alarms caused by statistical variations of the background should be exceedingly rare (fewer than one in one billion occupancies).

The false alarm rate should be specifically tested as part of acceptance testing of a system.

Summary

Background, speed, spacing, shielding, source intensity, and false alarm rate must be specified when determining the required sensitivity of an RPM. A purely hypothetical sample sensitivity requirement is provided below, which is drawn from other examples provided in literature[3,4,5]:

> The RPM shall provide a 50% alarm probability or higher on a sphere of metallic uranium enriched to 90% 235U weighing 1 kg when placed in the centerline in the bed of a standard pickup truck traveling through the portal at 8 km/h in a radiation background of 150 nSv/h or higher. Spacing between the faces of the pillars shall be 4.2 m or greater. The RPM shall produce fewer than 1 false alarm in 1,000 occupancies generated by artificially blocking the occupancy sensors for 4 s, with 10 s between occupancies.

A facility will have to determine the appropriate sensitivity and threat material for its needs.

Installation Considerations

When installing RPMs, the following characteristics should be considered:

Bypass prevention: RPMs should be installed at facility choke points to prevent bypassing or avoiding the RPM, including preventing pedestrians from passing a source around the RPM. If a radiation source passes near an RPM but the carrier is not detected by the occupancy sensor, the measured background will increase; since no occupancy was created, there would be no alarm.

Electronic and cyber-aggression: The RPM and occupancy sensors should be protected against electronic threats:

- External wiring should be sealed in concrete or placed in a metallic conduit.
- Door switches to detect if someone opened the RPM; an alert or notification should be generated on the CAS screen upon each door opening and closing.
- Electronic and computer systems should be located within a limited access room.
- Backup batteries should be available in case of power loss.

In addition to electronic aggression, the network is a new attack surface:

- The default password should be changed.
- The number of people who know the password should be limited.

- In case of remote control through ethernet:
  - o When no operation is needed, the session should be closed.
  - o The cybersecurity expert must be informed of the RPM remote control.

Physical aggression: RPMs need to be firmly bolted to the floor, and crash protection (e.g., bollards, protective railings) needs to be positioned to prevent damage by vehicle, forklifts, etc.

Climate protection: Long term exposure to the environment can damage detectors and/or electronic components. Placing the RPM components under some type of roof to block direct sunlight, rain, hail, and snow will considerably lengthen the lifetime of installed equipment.

Factory Acceptance Test/Receipt Inspection

This section details the testing that should be performed on a first article or randomly selected subset of equipment to conclusively demonstrate the performance of the as-built equipment. Tests should be conducted under worst-case conditions rather than best-case or average conditions. Receipt inspection should be conducted in the final RPM location after installation.

Sensitivity Test

The first test performed should be to demonstrate that the RPM will generate an alarm for the intended radioactive sources. If the test source has been appropriately selected, it can be relatively straightforward to repeat the test at different sensitivity levels to ensure that the most practical settings are used. It is important to allow sufficient time between each walk- or drive-through to allow the system to update its background and the alarm threshold.

However, prior to beginning the repeated test runs for sensitivity, the conditions defined in the "Performance Considerations" section should be specified. In particular:

- For pedestrians, the most unfavorable location on the human body should be determined. A realistic shielding material around the target source should be used and the tests should be conducted using a fast walking pace.
- For vehicles, the most self-shielded location within a standard vehicle should be determined. The frame, body, brake rotors, and engine all provide significant amounts of shielding that an adversary could take advantage of.

Ideally, multiple walk- and drive-throughs would be conducted with the source in different locations to determine which location provides the lowest count rate on the RPM (see Section 2). This location is then used for all subsequent testing (Figure 5).

After the least sensitive location is determined, repeated test runs should be conducted to determine the RPM's probability of detection against the selected source. Table 2 shows the number of test runs and successes required to show a desired probability of detection at a 95% confidence interval.

Table 2. Number of trials and successes required to demonstrate the desired probability of detection using a 95% one-sided confidence interval calculated using the Wilson confidence intervals[6]

No. Trials	Number of detections required to demonstrate a probability of detection (95% confidence interval)				
	0.5	0.7	0.8	0.9	0.95
10	8	10	—	—	—
20	14	18	19	—	—
30	20	26	28	30	—
50	31	41	45	49	—
60	37	48	54	58	60
100	59	78	87	95	99

For example, to demonstrate with 95% confidence that a system has a probability of detection of 0.5 or greater in 10 trials, the system must alarm in at least 8 of those 10 trials. The "95% confidence" is used to ensure that an under-performing system doesn't get "lucky" and happen to pass the test. Repeating a test ten times is usually logistically feasible, and 8 of 10 allow for some missed detections due to natural variation between trials. Confirming high probabilities of detection such as 0.9 or 0.95, while desirable from a security standpoint, require high numbers of trials. For example, a probability of detection of 0.95 with 95% confidence requires a correct decision in 60 of 60 trials; conducting a test sixty times with no margin for error can become operationally burdensome. But as such a sensitivity test may be performed only once when installing the RPM, it may be worthwhile to allot sufficient time to perform the test.

False Alarm Test

The aim of the false alarm test is to demonstrate that the alarm threshold selected above will produce an operationally acceptable false alarm rate. The false alarm test must be performed using RPM settings identical to what was used to demonstrate the appropriate sensitivity in the sensitivity test, and without radioactive material nearby.

From the definition of the alarm rate given in Section 2 (*AL=BKG+ n√BKG*), the expected false alarm rate according to *n* is given in Table 3.

Table 3. Expected false alarm rate according to n.

n	Average false alarm rate
0	1 every 2 walk-through
1	1 every 6 walk-throughs
2	1 every 44 walk-throughs
3	1 every 741 walk-throughs
4	1 every 31 574 walk-throughs
5	1 every 3 488 556 walk-throughs

Ideally, for vehicle RPMs, a conveyance would be used with no source in it (e.g., an empty truck) because this best represents the real-world conditions. For pedestrian RPMs, the false alarm test can be performed by walking through the RPM hundreds (or thousands) of times and verifying that no alarms occur.

Alternatively, a conservative approach using "ghost occupancies" can be easily performed. Ghost occupancies can be generated by either physically blocking the occupancy sensors or triggering an occupancy electronically in the RPM hardware. Using ghost occupancies can be a conservative approach because they do not introduce the background suppression effects associated with the presence of a vehicle.

When conducting false alarm tests of an RPM, it is important to (1) use occupancy durations that are representative of an actual occupancy and (2) provide sufficient time between occupancies to allow the system to, at a minimum, partially update its background.

Fault Test

Many RPMs contain fault logic to alert operators if something is outside of the expected, normal operating conditions. These faults and the conditions that trigger them vary among RPMs. Table 4 lists common faults and their test methods.

For spectroscopic portals, other faults that may exist and should be checked are

- calibration problems with the gamma detector and
- insufficient counts for an identification.

Each fault should be introduced and the response observed to verify that the operator is able to take corrective action. The monitoring system should provide a warning indication when there is a change greater than a level at which the monitor no longer meets the detection requirements.

Review Settings Documentation

After the testing is complete and satisfactory results have been obtained, the complete system settings should be recorded for future comparison after maintenance actions have been performed.

Daily Testing / Functional Test

The following are suggested tests to be run daily or at the beginning of each shift. They are used to document the proper operation of the RPM at a basic level. Each facility will have compensatory measures and return-to-service actions if an RPM does not pass the daily or functional checks.

Typically, the test with one gamma source and one neutron source (as appropriate) is sufficient to confirm system operation at the start of a day or shift.

Table 4. Common fault conditions and tests examples

Fault	Object	Test
Background too high	Detect artificial increase of the background	Without triggering an occupancy, gradually move a radioactive source toward the detection zone until the fault is generated
Background too low	Detect sensitivity degradation caused by potential detector malfunction	Set the fault level to an abnormally high value and wait until natural background fluctuations dip below that level
Nonresponsive occupancy sensor	Detect degradation of the occupancy sensor	Unplug/disconnect the occupancy sensor at the RPM and see if a fault is generated
Tamper indication or cabinet door open	Detect intrusion	Open cabinet door; confirm alert at the CAS
Communication failure	Detect electronic or cyber-aggression of the communication between the RPM and the control station	Disconnect the RPM from the CAS and observe the response on the CAS

Sensitivity Test

This test should be performed using the target itself. It could be logistically difficult to bring actual threat material to the RPM. Surrogate sources can be used in place of threat material in those cases, and this is described in more detail in Annex 2: Test Sources, and in some IEC standards[7]. The source should be passed once through the monitor (conditions can be different from the receipt inspection/sensitivity test), and the following should be recorded:

- Confirmation that an alarm was generated
- The background before the occupancy
- The maximum count rate reported during the occupancy

The daily check of the background and count rate can be useful to detect any long-term drift of efficiency and allow for preventive maintenance.

Occupancy Sensor Test

Because proper RPM operation requires that the occupancy sensors are working, it is important to also verify that an occupancy is created when a pedestrian or vehicle (or another object) occupies the portal. For vehicle RPMs, some systems measure the speed of the vehicle, which can inform the algorithm; if present, the speed should be verified as well. The occupancy sensor test can be combined with the aforementioned sensitivity test.

Communications Test

In addition to providing an alarm locally (if desired), verify that an occupancy and alarm are registered at the CAS as expected. In addition, verify also that associated systems are activated (audible alarm, barriers or turnstile control blocked).

Review of Fault Log

At the CAS, ensure the RPM and associated equipment (e.g., detectors, cameras, gate arms, other sensors) are reported as working properly. Any faults should be logged, and if they persist, compensatory action should be taken as necessary.

Confirmation of Important Settings

Verify that the settings such as the alarm threshold and the minimum and maximum background count rate are those expected; this task is made easier if the settings are stored at the CAS.

Annual Maintenance / Routine Operational Evaluation

The following is a list of suggested procedures to perform annually, or more often if desired or recommended by the equipment manufacturer. These tests are performed on equipment or aspects of the equipment that are assumed to degrade slowly and that may not be caught by the daily testing regime described in Section 5.

Cleaning/Check for Rust

Remove bees, rodents, rust, or any other unwelcome objects or materials to the RPM. Remember to treat the problem (e.g., improperly sealed cable pass-throughs) and not just the symptom (e.g., removing insects from the RPM). In harsh outdoor environments such as intense sun or salty air, checking for rust may need to be performed quarterly.

Battery Health Checks

Many RPMs contain a battery for continuous RPM operation in case site power is lost. The battery should be load tested to verify that sufficient voltage and amperage can be provided. Replace the battery if the available power is less than specified.

Gamma Calibration

It is important to calibrate detectors to ensure that the energy measured by the detector is going into the correct energy bin for the algorithm to process. An incorrect calibration results in a worse signal-to-noise ratio and adversely affects the algorithm's performance. A calibration usually involves measuring a known radiation source (e.g., ^{137}Cs) and adjusting a voltage parameter to place the observed radiation peak into the desired energy bin.

The calibration can drift because of temperature (i.e., the detector's response changes as a function of temperature) or over time as the electronics change subtly. Some systems perform an autocalibration based on existing peaks in the naturally occurring radiation background, whereas others require placement of a source on or near a detector. A manual check of the calibration should be performed at least annually.

Spectroscopic systems rely on the correct identification of occasional weak peaks in the spectrum and are sensitive to changes in calibration. For these systems, an annual calibration check may not be frequent enough to ensure that the system is operating correctly. For example, a calibration performed in the hot summer months may not be correct during the cold winter months. Manufacturers should be consulted to address this condition, and their solutions should be independently verified.

Neutron Calibration

Since the neutron detectors only alarm based on the presence of neutrons (and the incoming energy of the neutrons is lost in the moderator), the calibration process is simpler. First, verify that the applied voltages are consistent with the manufacturer's recommendations; the actual value varies based on the manufacturer and the detector type. This is usually conducted with a voltmeter and a high volage probe, or sometimes the RPM electronics can provide a direct readout. Second, perform a sensitivity test, as described in Section 6, to verify that overall performance is maintained.

Sensitivity Testing

Annual or semi-annual sensitivity testing should be performed to confirm that the overall sensitivity of the RPM is as required. Unannounced testing, with adequate controls, is a good way to test the entire system, including operators.

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References

1. IAEA Nuclear Security Series No. 13: *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities*, INFCIRC/225/Revision 5, 2011. DOI: 10.61092/iaea.ko2c-dc4q
2. York, R. L., and Fehlau, P.E., 1997 *Update for the Applications Guide to Vehicle SNM Monitors*. LA-13247-MS. DOI: 10.2172/468602
3. ASTM International, *Standard Guide for Application of Radiation Monitors to the Control and Physical Security of Special Nuclear Material*, C1112-99(2005), withdrawn in 2014.
4. ASTM International, *Standard Guide for In-Plant Performance Evaluation of Automatic Pedestrian SNM Monitors*, C1169-97(2012), withdrawn in 2021.
5. ASTM International, *Standard Guide for In-Plant Performance Evaluation of Automatic Vehicle SNM Monitors*, C1236-99(2005), withdrawn in 2014.
6. Wilson, E. "Probable Inference, the Law of Succession, and Statistical Inference." *Journal of the American Statistical Association*, volume 22, issue 158, pages 209–212. DOI: 10.2307/2276774
7. International Electrotechnical Commission, Radiation protection instrumentation: *Installed radiation portal monitors (RPMs) for the detection of illicit trafficking of radioactive and nuclear materials*, IEC 62244:2019.

References 1-5 have been withdrawn for unknown reasons, but the authors still find the content valuable and accurate.

Annex 1: Sample Forms

RPM Evaluation Data Form

Name: Date: Location:

RPM INFORMATION

Manufacturer: ______________ Serial #: _________ RPM type: ____________________

Setting 1 name: ____________ Value: ________ Setting 2 name: ____________ Value: ________

Setting 3 name: ____________ Value: ________ Setting 4 name: ____________ Value: ________

(Include more settings on back if necessary.)

Background reading: Background duration:

SENSITIVITY TESTING:

Source used: ________________________ Source location: ______________________________

Description of source strength (e.g., grams, µSv, Bq): ________________________________

Number of trials: _____________________ Number of detections: ______________________

Result (circle one): PASS FAIL

FALSE ALARM TESTING:

Occupancies generated by (e.g., empty vehicle, hand, electronic): ______________________

Number of trials: _____________________ Number of false alarms: _____________________

Result (circle one): PASS FAIL

RPM Daily Test Form

Name: Date: Location:

RPM serial #: _________ RPM type: ___________ Source used: ____________________

Count rate: ______________ In agreement with the reference count rate: YES NO

Occupancy recorded at CAS: YES NO Alarm generated: YES NO

(If either of the above answers is "NO," contact maintenance immediately and implement compensatory measures.

Faults on CAS: YES NO If yes, explain: ______________________________________

Annex 2: Test Sources

Many RPMs count the number of photons above a lower-energy limit to calculate the count rate. This detection threshold may vary over time because of photomultiplier aging or electronic drift and change the sensitivity. A sensitivity test with only a high-energy source is not enough to detect a change.

As an example, ^{137}Cs sources are often mistakenly used for sensitivity tests. The gamma-ray energy spectrum of ^{137}Cs and uranium-plutonium mixed oxide (MOX) in a plastic scintillator are shown in Figure 6. The RPM counts the number of energy deposits above 30 keV to calculate the count rate. If the lower energy limit drifts up to 50 keV, the count rate of a 137Cs source would decrease by 6%, whereas the count rate of MOX would decrease by 28%.

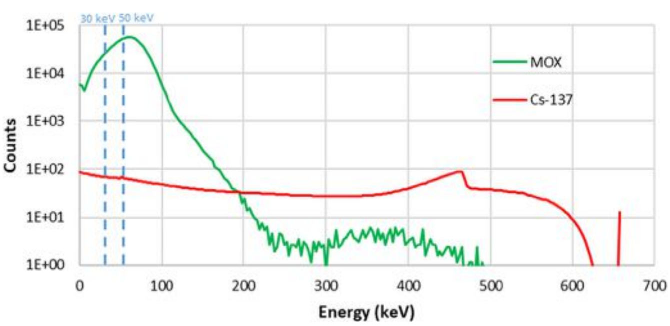

Figure 6. Energy spectrum of 137Cs source and MOX in plastic scintillator (simulation).

Surrogate sources can be used in place of nuclear material, but not just any. The goal is to find radioactive source(s) which produces gamma-rays or neutrons with similar properties as for the target source (both energy and fluence). Here are some surrogate source examples:

- ^{57}Co instead of ^{235}U. 57Co has a primary emission at 122 keV, compared to ^{235}U's 186 keV peak. Thus, detection of ^{57}Co can give a reasonable estimate of a detector's ability to detect ^{235}U. Unfortunately, the half-life of ^{57}Co is only 270 days, so it must be replaced every 1 to 2 years.
- ^{133}Ba instead of 239Pu. ^{133}Ba has a primary emission peak at 356 keV, slightly below the 375 and 414 keV pair commonly associated with ^{239}Pu. With a half-life of 10.5 years, barium-133 is a reasonable substitute for detection of ^{239}Pu.
- ^{252}Cf for neutrons. ^{252}Cf emits neutrons as it undergoes spontaneous fission, and the resulting neutron spectrum closely resembles that of ^{240}Pu, making it a good surrogate. However, its half-life is only 2.65 years, requiring replacement every few years.

Sometimes it might be necessary to use two surrogate sources. For example, MOX is a mix of uranium, plutonium, and americium due to the ^{241}Pu decay to ^{241}Am, so the surrogate should be composed from a ^{133}Ba source and an ^{241}Am source, as shown in Figure 7. It is difficult to choose the surrogate source activity because there is not direct relation between nuclear material mass and surrogate source activity (the gamma rays fluence of nuclear material depends on many parameters: mass, chemical composition, shape, shield). Based on simulation or experimental measurement, an expert can calculate the required surrogate source activity according to the target defined.

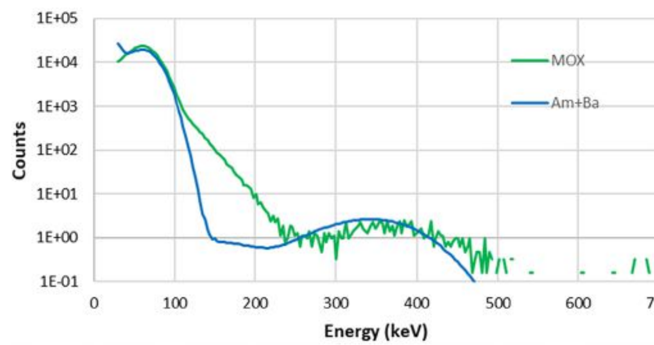

Figure 7. Comparison between simulated gamma-rays spectra of MOX and surrogate source (Am + Ba), with a plastic scintillator

Defining the Test Source

Different references are available as guidance for selecting a test source.

The *1997 Update for the Applications Guide to Vehicle SNM Monitors* (available at https://www.osti.gov/biblio/468602) lists 10 g of low-burnup plutonium or 1,000 g of highly enriched uranium as worst-case detection sensitivities[2]. Note that the material type, geometry, vehicle speed, background, and object placement are all carefully specified because these can significantly affect RPM performance.

Rather than describing a source and test conditions, the *Technical Capability Standard for Radiation Portal Monitor Systems with Energy Analysis Capability* (available from https://www.dhs.gov/sites/default/files/publications/radiation-portal-nseac-tcs-11-2019.pdf) lists the fluence rate of the source at the detector assembly. This is the number of gamma rays that impinge upon the detector face per square centimeter per second. Testing using this method is less prescriptive for the source and shielding, but it requires additional analysis on the part of the testers to provide the correct test conditions.

RPM Life Cycle Maintenance

In 2001, the US Department of Energy (DOE) issued the Nuclear Facility Maintenance Management Program Guide for Use with DOE Order 433.1. It is available here: https://www.directives.doe.gov/directives-documents/400-series/0433.1-EGuide-1/. Later versions have updated, modified, and simplified in this document, but the authors believe this 2001 version provides the best, most detailed guide to maintaining equipment in a nuclear facility.