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Research

OPERATION OF RADIATION PORTAL MONITORS OF SPECIAL NUCLEAR MATERIALS AT NUCLEAR SITES IN TERMS OF RELIABILITY

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ABSTRACT

Two often used operational algorithms of radiation portal monitors are reviewed taking into account specific conditions of physical protection systems at nuclear sites. Reliability parameters such as probability of no failure and false alarm rate of both types of radiation portal monitors are evaluated. As a result some offers on application of radiation portal monitors working in different modes are suggested.

INTRODUCTION

Nowadays one of the most important security issues is concerned with a reliable radiation control in physical protection systems of nuclear sites (or PPS). The basic means of it are radiation portal monitors of special nuclear materials (or RPMs). RPMs are complicated technical systems meant for detection of special nuclear materials (or SNM). Gamma and neutron radiation is detected when SNM are being smuggled through entry control points (or ECPs). Thorough requirements are described in GOST R 51635-2000 «Nuclear material radiation monitor. General specifications».

The main technical characteristics of RPMs that influence reliable radiation control are:

• Detection threshold of SNM, which is a minimal mass of SNM sample in a minimal emission configuration that RPM must detect with a given probability.

• False alarm rate of RPM, which is a periodicity of alarms generated with no source of radiation in a control space.

• Mean time between failures (or MTBF). Failure is a trouble leading to the mismatch of detection threshold of SNM and false alarm rate in comparison with values specified in GOST R 51635-2000.

The principle of SNM detection with RPM is a comparison of emission level of an object being moved through the control space of RPM with a background gamma or neutron radiation rate. The detection threshold may be found as:

$$N_{thr} = B + k \cdot \sqrt{B} + p \quad (1)$$

where N_{thr} is a detection threshold, B – mean background counting rate, k – detection threshold array factor, p – coefficient of dissymmetry of Poisson impulse distribution.

Detection threshold array factor k is defined empirically. It depends on background radiation level at ECP and its variations, number of detection units, width of space of control, control time, etc.

During gamma radiation registration mean background counting rate B can exceed 1000 impulses per second. In this case, impulse distribution approximates normal distribution. Therefore, coefficient p can be neglected. In many cases mean neutron background counting rate B equals several impulses per second, so coefficient p for neutron radiation usually equals 2.

Thus, to detect SNM during its movement through the control space RPM should perform following procedures:

1. Collect background radiation level B measurement statistics when radiation sources or outside objects are in the control space of RPM.

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2. Perform detection of radiation level of an object during its movement through the control space *N*.

3. Compare a level of radiation from an object *N* with a detection threshold N_{thr} defined with the formula (1) to check the detection criterion.

4. Provide a guard with a respective sound or light alarm signal if a detection criterion is hold ($N_{thr} \geq N$). In PPS RPMs may be connected in a local network. In this case, alarm messages are received and displayed on a separate automated working station (AWS).

At the same time, type I and type II errors are not ruled out. Type I errors (or errors which happen when RPM initiates a false alarm) may happen due to the following reasons:

1. Even when the object is out of control zone false alarms may occur statistically especially when there is a large number of passes or when RPM works for a long time without being switched off (Russian national standard GOST R 51635-2000). It may be related with background radiation level variations, electronic noises in RPM components or accumulation of random mistakes, etc.

2. As RPM's sensitivity to radiation level variations increases false alarm rate grows. In this case the main cause is an effect of a partial shielding of registered background gamma radiation by an object itself: when it crosses a control zone of RPM a counting rate of detection units decreases. After an object has left a control zone detection units counting rate gets back to its normal level. This can be considered as an appearance of radiation source by RPM, an alarm may be generated.

RPMs are often integrated with a wide variety of controlled blocking devices (turnstiles, lifting gates, etc.). When smuggling of SNM is detected RPM generates an alarm as well as a control signal to block a barrier in order to delay an adversary. Therefore, it's necessary to find ways to decrease a false alarm rate so that these alarms don't block people, vehicles or cargo by mistake.

Type II errors occur when an object containing radiation source crosses a control zone generating no alarms due to the following reasons:

1. A counting rate may be not enough to meet a criterion of detection. This may be initiated by a need to control a wide space (according to Russian national standard GOST R 51635-2000 the distance between pillars should not exceed 0.8 m for pedestrian RPMs, 3 m for vehicle RPMs and 6.2 m for rail transport RPMs), a lack of detection units, their design and arrangement features, presence of materials shielding gamma rays and neutrons in a controlled object, an exceeding of speed by an inspected object (according to GOST R 51635-2000 a speed of pedestrians should be 1.0-1.2 m/s, a speed of vehicles should make 10±2 km/h, a speed of rail transport should be about 25±5 km/h), etc.

2. Performance and reliability of RPM are unsatisfactory. Usually an inspection time is limited because of a heavy traffic. Thus, RPM should have a high performance and reliability to execute an inspection cycle, generate an alarm with a given confidence and return to the initial state ready to inspect the next object.

3. Settings and algorithms of operation of RPM are applied taking no specific conditions of exploitation into account. For instance, in real operational conditions at nuclear sites RPMs may be located in areas with heightened background radiation levels. This fact may decrease a probability of detection of small amounts of low-active SNMs.

So, to ensure reliable radiation control in PPS it is necessary to decrease a probability of type I and type II errors. This may be achieved only by development of RPM's design and algorithms of its work. On the one hand, the detection threshold should be lowered, whereas on the other hand a false alarm rate needs to be decreased.

RESULTS AND DISCUSSION

As it was mentioned before, to detect SNM by RPM it is required to measure a surrounding background gamma and/or neutron radiation level without any objects within a control zone, then measure a radiation level of controlled object and, finally, compare them.

Thereupon, a principle of operation usually stipulates two basic modes which are background radiation detection mode and inspected object radiation mode.

Background radiation detection mode may be realized by manufacturers in different ways, they are:

• A single background radiation measurement during precomissioning or maintenance works and recording it afterwards.

• A background radiation measurement after every enabling or reboot of RPM.

• A background radiation measurement after every enabling or reboot of RPM and update of its values regularly during RPM's work.

• A measurement of instantaneous value of

background radiation before every pass of an inspected object. This value is defined as a counting rate integral accumulated during a given time before an inspected object enters a control space of RPM.

An update of values of background radiation may be realized in a couple of ways: new value overwrites an old one, averaging, moving averaging. The process of SNM detection heavily depends on the method or the algorithm chosen by a manufacturer of RPM.

After RPM has measured a background radiation level, it may work in two ways: RPM switches to the constant detection mode and measures a radiation in a control space or stays in a standby mode renewing a background radiation level in its memory and waiting for an inspected object to appear in a control space (automatic detection mode). Described operational algorithms are shown on Fig. 1 and 2 respectively.

A switch from a standby mode to a detection mode and vice versa in an automatic detection mode can be induced by a control signal from external devices, for instance, intrusion sensors, elements of access control system, guards control panel, etc. A method when a control signal is generated by a guard or someone else is not usually used in PPS due to the so called human factor.

Commonly those external devices that form a control signal to switch RPM to a detection mode are intrusion sensors that work on different physical principles i.e. infrared, microwave, ultrasonic, etc. In this case the

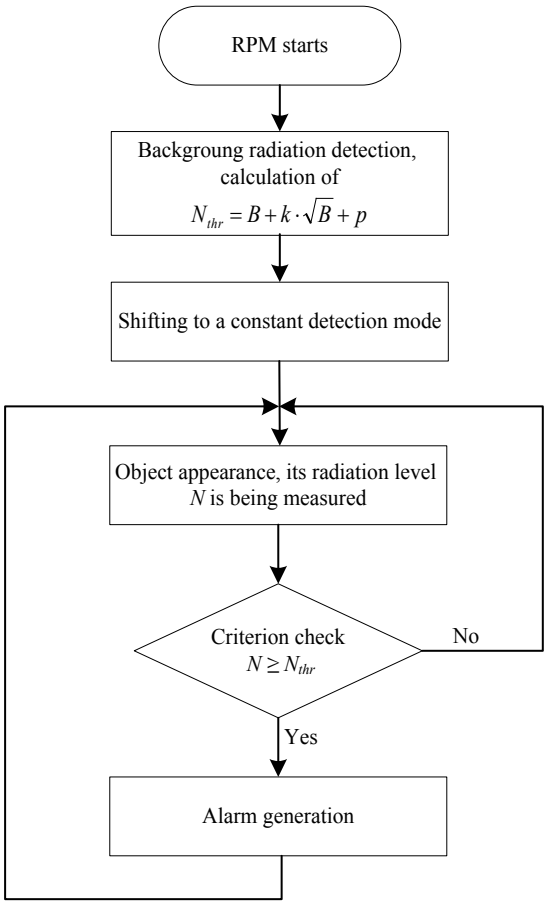

Fig. 1 Operational algorithm of RPM in a constant detection mode.

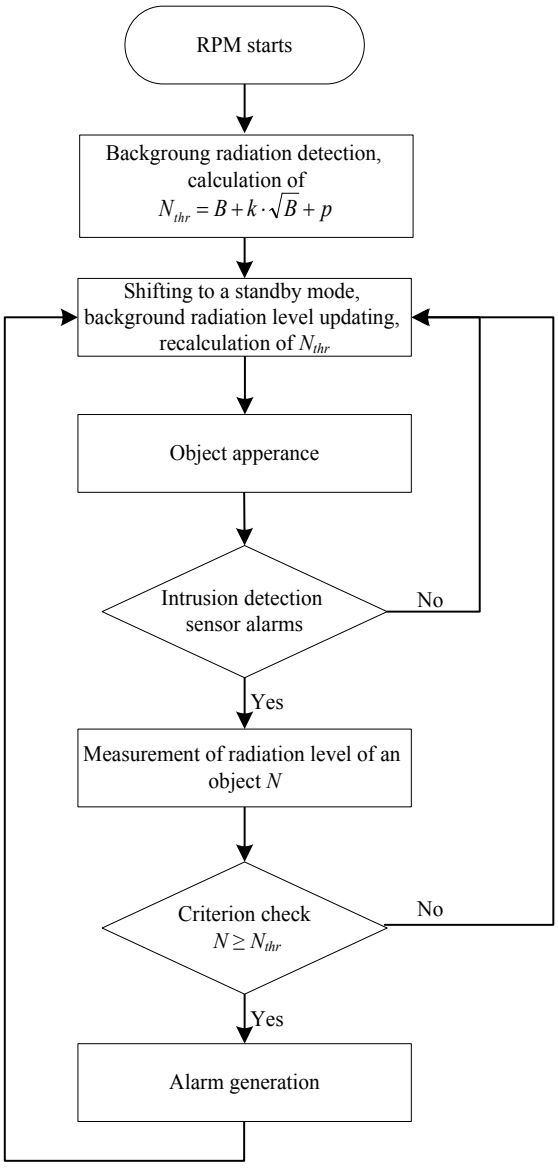

Fig. 2 Operational algorithm of RPM in an automatic detection mode.

most important criteria are their speed of operation and reliability because if a signal is not received by a processor unit RPM will not be able to switch to a detection mode. A speed of operation is an ability to generate an alarm in a minimal time and then switch to a standby mode before an inspected object has left a control space. It is especially important when RPM is integrated with controlled blocking devices and there is a heavy traffic (people or vehicle) through its control space.

Calculation of Basic Reliability Parameters of RPM

Let's have a look at how a certain mode of operation of RPM (constant detection mode and automatic detection mode) affects basic reliability parameters of its work namely MTBF and false alarm rate.

To calculate those parameters it is required to observe RPM not as a separate device but as an element of an automated PPS. An automated PPS in both cases has a sequential structure and consists of RPM itself, lower level controller, upper level controller and guards control panel to display alarms (Ushakov, 2008). In addition to elements named above RPM that works in an automatic control mode has an intrusion sensor. Functional schemes of RPMs that work in a constant detection mode and an automatic detection mode are shown on Fig. 3 and 4 respectively (Shyshmaryov, 2010).

Lower level controller (LLC) is meant for primary processing of signals that come from RPM, intrusion sensors and other devices, controlling external devices (turnstiles, roadway gates, locks, traffic lights, etc.) and communication with upper level controller.

Upper level controller (ULC) is meant for data collection from lower level controllers, data storage and remote devices control.

Guards control panel (GCP) is required to display graphic data about work of automated PPS, analyze whether alarm is true of false, control and adjust components of automatic PPS.

Let's calculate MTBF for both variants of system architecture. MTBF of components of an automated PPS (T_i) specified in maintenance documentation are used as an initial data for calculation (Table 1). Failure density of components of automated PPS λ_i is calculated by formula $\lambda_i=1/T_i$ (Shklyar, 2009).

Taking into account functional scheme of RPM that works in a constant detection mode, MTBF and failure density may be calculated as:

$$\ddot{e}_s^{const} = \ddot{e}_{RPM} + \ddot{e}_{LLC} + \ddot{e}_{ULC} + \ddot{e}_{GCP} = 0.000083 + 0.000011 + 0.000011 + 0.000019 = 0.000124\ h^{-1}$$

$$T_s^{const} = \frac{1}{\ddot{e}_s^{const}} = \frac{1}{0.000124} \approx 8064\ h$$

To calculate reliability parameters for RPM that works in an automatic detection mode it is necessary to consider presence of intrusion sensor:

$$\ddot{e}_s^{auto} = \ddot{e}_{sensor} + \ddot{e}_{RPM} + \ddot{e}_{LLC} + \ddot{e}_{ULC} + \ddot{e}_{GCP} = 0.000017 + 0.000083 + 0.000011 + 0.000011 + 0.000019 = 0.000141\ h^{-1}$$

$$T_s^{auto} = \frac{1}{\ddot{e}_s^{auto}} = \frac{1}{0.000141} \approx 7092\ h$$

To calculate a probability of no failure for both reviewed modes of work it is required to tabulate a function $P_s(t) = \exp(-\ddot{e}_s \cdot t)$ at an interval between 0 and 10 000 hours (Polovko and Gurov, 2006). The graph is shown on Fig. 5.

As seen on Fig. 5 probability of no failure of system that works in an automatic detection mode is a bit lower due to the fact that this kind of systems contains more elements than system working in a constant detection mode.

Then analysis of probability and rate of false alarms is to be executed for both modes of work.

To evaluate them let's consider a system that contains two elements (RPM itself and an intrusion sensor) because probability of false alarms that can

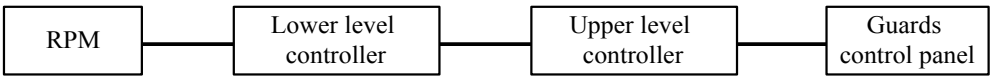

Fig. 3 Functional scheme of RPM working in a constant detection mode.

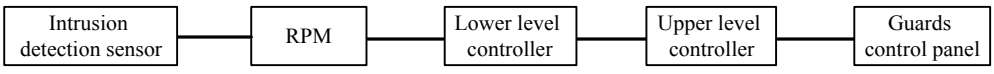

Fig. 4 Functional scheme of RPM working in an automatic detection mode.

Table 1. Initial data for MTBF calculation.

	Intrusion sensor	**RPM**	**LLC**	**ULC**	**GCP**
MTBF of components T_i, h	60000	12000	87600	87600	52560
Failure density of components of an automated PPS λ_i, h^{-1}	0.000017	0.000083	0.000011	0.000011	0.000019

be induced by controllers or guards control panel is negligibly small taking into account their design and technological features.

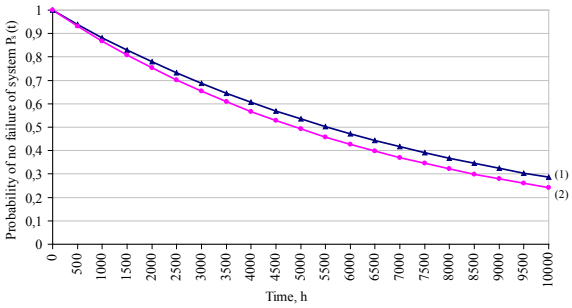

Fig. 5 Function of probability of no failure of system $P_s(t)$: 1 – for constant detection mode; 2 – for automatic detection mode.

According to GOST R 51635-2000 false alarm rate for pedestrian and vehicles RPMs should not exceed 1 false alarm per 1000 passes or 1 false alarm during 8 hours of permanent work.

Following features of exploitation of PPS should be considered:

• As usual, access control is implemented at nuclear sites. It includes measures that strictly limit a number of transportation that can enter certain ECP as well as a number of people. Therefore, mean number of passes per day is almost constant and can be easily evaluated.

• Passes are being performed irregularly during a workday. A maximum number of passes is made at 8-9 a.m. and 4-5 p.m. In other time intensity of passes is much lower.

• Access control should be organized so that all personnel can enter a site in a certain period of time (about 10-20 minutes) and no queues appear. It can be achieved by having enough gates and RPMs at ECPs.

Therefore, to perform a calculation an experimental distribution of passes through one pedestrian and one vehicle RPMs is considered. An experiment was taken during the day (24 hours) since 12 p.m. at one of nuclear sites. Results are shown in table 2.

In case of RPMs working in a constant detection mode it is impossible to define actual number of passes without access control system devices. Besides, false alarm can happen at any moment (not only when an inspected object is in a control space). That is why it is reasonable to assume that a false alarm rate of RPMs that work in a constant detection mode λ_{fa}^{const} does not exceed 1 false alarm during 8 hours of permanent work.

Let's evaluate probability of false alarms of RPM working in a constant detection mode by tabulating following function at an interval from 0 to 24 hours (Polovko and Gurov, 2006):

$$Q_{fa}^{const}(t) = 1 - \exp(-\lambda_{fa}^{const} \cdot t) \quad (2)$$

A graph showing results for RPM working in a constant detection mode is on fig. 7. As for RPM that works in an automatic detection mode a process of control is active only when an inspected object moves through a control space. A number of passes that have been made can be defined quite accurately.

It is important that an intrusion sensor is usually a device that has its false alarm rate specified by a manufacturer in a technical documentation for certain exploitation conditions and nuisance environment. In real conditions intensity of nuisance can significantly exceed values specified in documentation. For the purposes of work false alarm rate is assumed 1 false alarm per 4 hours of permanent work.

So, for RPM that works in a constant detection mode it is reasonable to assume that false alarm rate $\ddot{e}_{fa}^{auto}$ does not exceed 1 false alarm per 1000 passes. In addition, because of the fact that number of vehicles and personnel having an access at a nuclear site is limited one thousand passes can be performed in more than 8 hours. False alarm rate of RPM that works in an automatic detection mode depends on intensity of passes: the frequently passes are the higher false alarm rate is. For intensity of passes is irregular dependence of false alarm rate from number of passes performed during monitored time will be like:

Table 2. Distribution of passes through one pedestrian and one vehicle RPMs.

Time, h	Number of passes per hour		Time, h	Number of passes per hour		Time, h	Number of passes per hour	
	people	vehicles		people	vehicles		people	vehicles
01:00	80	10	09:00	30	25	17:00	250	20
02:00	20	8	10:00	20	20	18:00	20	10
03:00	8	8	11:00	20	20	19:00	10	10
04:00	8	8	12:00	200	20	20:00	10	8
05:00	8	8	13:00	200	25	21:00	10	8
06:00	15	8	14:00	20	20	22:00	10	8
07:00	250	30	15:00	20	10	23:00	10	8
08:00	80	30	16:00	100	25	24:00	100	10

$$\lambda_{fa}^{auto}(t) = \frac{N_{pass}}{1000 \times T_{sum}}\ ,, \quad (3)$$

where N_{pass} – total number of passes performed during total observation period T_{sum}.

On basis of initial data specified in table 2 graphs showing function of false alarm rate of RPM working in an automatic control mode of time of experiment are formed (Fig. 6).

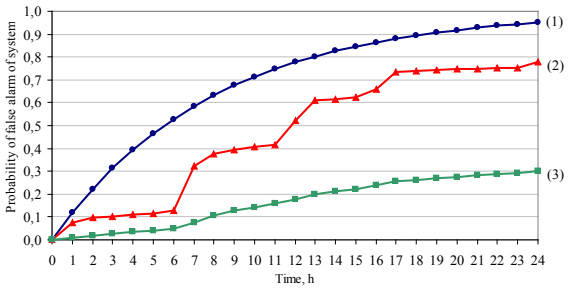

Fig. 6 False alarm rate $\lambda_{fa}(t)$ of RPM working in an automatic detection mode: 1 – for pedestrian RPM; 2 – for vehicle RPM.

A false alarm of a system working in an automatic detection mode can be caused by following events: simultaneous false alarm of an intrusion sensor and RPM, false alarm of RPM during the pass with an intrusion sensor working normally. A false alarm of an intrusion sensor with RPM working normally will not cause a false alarm of a system. It will only make RPM switch to a control mode when an inspected object is off a control space. Information about states of operability of a system working in an automatic mode are specified in table 3, where P is a probability of normal operation of an element, Q is a probability of false alarm of an element.

Table 3. States of operability of a system working in an automatic mode.

Description of state of elements of a system (intrusion detection sensor and PRM)	Probability of a state	State of a system
Intrusion detection sensor and RPM operate normally	$P_{sensor.} \square P_{RPM}$	Normal operation
Intrusion detection sensor initiates false alarm, RPM operates normally	$Q_{sensor.} \square P_{RPM}$	Normal operation
Intrusion detection sensor operates normally, RPM initiates false alarm during a pass	$P_{sensor.} \square Q_{RPM}$	False alarm
Intrusion detection sensor and RPM initiate false alarms simultaneously	$Q_{sensor.} \square Q_{RPM}$	False alarm

Thereby probability of false alarm of a system working in an automatic mode will be equal to a sum of probabilities of states leading to a false alarm of a system (Shklyar, 2009):

$$Q_{fa}^{auto}(t) = P_{sensor} \cdot Q_{RPM} + Q_{sensor} \cdot Q_{RPM} = \exp[-\lambda_{fa}^{sensor} \cdot t] \cdot \left(1 - \exp[-\lambda_{fa}^{RPM}(t) \cdot t]\right) + \left(1 - \exp[-\lambda_{fa}^{sensor} \cdot t]\right) \cdot \left(1 - \exp[-\lambda_{fa}^{RPM}(t) \cdot t]\right) \quad (4)$$

Let's evaluate probability of false alarm of a system that works in an automatic mode by tabulating function (4) at an interval between 0 and 24 hours taking into account values of false alarm rate defined with a use of formula (3). The graph is shown on Fig. 7.

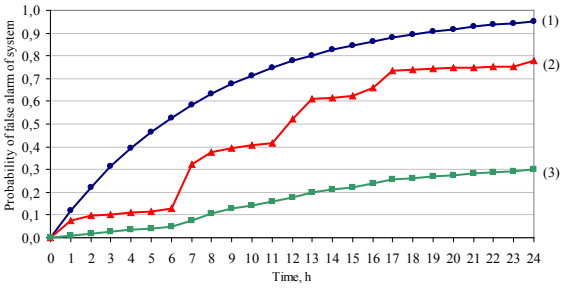

Fig. 7 Function of probability of false alarm rate $Q_{fa}(t)$: 1 – RPM that works in a constant detection mode. 2 – Pedestrian RPM that works in an automatic detection mode. 3 – Vehicle RPM that works in an automatic detection mode.

As seen on fig. 7, probability of false alarm of RPMs that work in either modes is a monotonically increasing function of time. For low intensity of passes probability of false alarm of RPM working in an automatic detection mode is significantly lower than probability of false alarm of RPM that works in a constant detection mode. Fast increase of intensity of passes leads to a noticeable increase of function of probability of false alarm.

CONCLUSIONS

In conclusion, PPS at nuclear sites can use RPMs working in both reviewed modes (automatic detection mode and constant detection mode). A solution whether use one or another type of RPMs should be made taking into account individual conditions of a nuclear site namely number of personnel, intensity of passes, access control requirements and timetable.

When intensity of passes is low it is reasonable to use RPMs that work in an automatic detection mode because their false alarm rate is expected to be lower in comparison with RPMs working in a constant detection mode.

Despite the fact that calculated probability of no failure of a system that works in an automatic detection mode is a bit lower that the one of a system working in a constant detection mode practically it has little influence due to regular maintenance of elements of system, use of modern intrusion detection sensors and having a little makeup time when it is necessary to repair intrusion detection sensors.

When RPMs are exploited at nuclear sites well-judged ECP design, a detection zone configuration and having an intrusion sensor chosen taking into account nuisance environment and physical principal of operation have primary importance.

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