Hand-foot monitors for nuclear plants based on scintillator–WLS–SiPM technology

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Abstract. The technology of charged particles detection by a plastic scintillator light from which is collected by wavelength shifting fiber (WLS) on Silicon Photomultiplier (SiPM) is widely used in high energy physics. We present in this article the new personnel surface contamination monitoring assembly based on that technology as a result of about two years R&D research. This assembly is used for contamination control of hands, feet and clothes at nuclear power plants, nuclear facilities and other objects that work with radioactive materials. Setup design, main parameters and its measurement procedures are presented. It has high efficiency to $\alpha$ and $\beta$ particles in wide energy range, large dynamic range, very good area uniformity and excellent temperature stability. Dynamic range of measured particle fluence rate equals: $1 \sim 10^6$ Hz·cm$^2$·min for $\beta$-module and $0.1 \sim 2 \times 10^4$ Hz·cm$^2$·min for $\alpha$-module. Variations of the module response in temperature range from $-20^\circ$C up to $+50^\circ$C doesn’t exceed 3%.

1. Introduction

Surface contamination meters and monitors are one of the mandatory devices at nuclear power plants, nuclear facilities, radiological laboratories, radiopharmaceutical factories and other objects where radioactive materials are used. Generally, these assemblies contain monitors for hand and foot and remote module for contamination control of clothes. It can be sensible to $\beta$–, $\alpha$–particles or $\gamma$–radiation. Requirements for these assemblies are set by standard IEC 61098 [1]. For Russian ones they should follow the standard of organization STO 1.1.1.02.004.1078-2015 [2].

Hand-Foot monitors producing up to now can be divided on two big groups: with gas usage and with plastic scintillators for $\beta$–particles and ZnS(Ag) scintillator films on clear plastic for $\alpha$–particles. It is possible to make mixed $\alpha$–$\beta$–detectors. Gaseous equipment can use Geiger-Muller counters like MKS–100A (STC Amplituda, Zelenograd, Russia – figure 1a) [3] or proportional gas-flow counters like Sirius–5AB (Canberra Inc., Meriden, USA – figure 1b) [4]. Both detectors are well known since the beginning of the 20th century and have well proven technology of production, possibility to cover significant areas that required for hand-foot monitors. But gaseous counters have such drawbacks as:

- big dead zones on the monitor’s active area and as a result high nonuniformity or high price – Geiger;
- high voltage – both;
- restricted lifetime due to leakage or degradation of working gas (limit for number of the registered impulses $\sim 10^9$) – Geiger;
- slow (dead time of the order of $10^{-6}$ s) – both;
- require additional gas flow equipment – proportional counter
- special complicated construction with super-thin walls for $\alpha$-particles – proportional counter

![Figure 1. Hand-foot monitors based on gas detectors: a) Geiger-Muller counters MKS-100A (STC Amplituda, Zelenograd, Russia) and b) proportional gas-flow counters Sirius-5AB (Canberra Inc., Meriden, USA).](image)

Advantages of scintillator based equipment are as follows: possibility to cover big areas without dead zones, shot duration of scintillation flash for $\beta$-particles 5–20 ns. But it is sensitive to ambient light and temperature: light output depends on temperature with coefficients from -0.15 %/K up to -0.55 %/K [5].

![Figure 2. Hand-foot monitors based on plastic scintillators: a) scintillator id read by PMT, RZB–04M (SPC Aspect, Dubna, Russia); b) scintillator is read by PMT via fiber, HandFoot–Fibre (RADOS GmbH, Germany); c) scintillator is read by SiPM via WLS fiber, RZBA–07D (SPC "Doza" Ltd, Zelenograd, Russia).](image)

Examples of hand-foot monitors with plastic scintillators are presented on figure 2. First one (RZB–04M [6]) is produced by SPC Aspect, Dubna, Russia (figure 2a). It uses PMT for reading plastic scintillator. Such decision has potentially not very good uniformity. In the HandFoot–Fibre monitors [4] produced by RADOS GmbH, Germany (see figure 2b) this parameter is significantly
improved by using fiber to collect light from scintillator to PMT. PMT is practically perfect optical detector but it has high price, relatively big size, require high voltage for operation (of about 1 kV), senstive to magnetic field and temperature.

Another alternative for PMT appeared recently – Silicon Photomultiplier. It is solid state photodetector with gain and detection efficiency similar to PMT, but it has much smaller size, lower operating voltage and lower cost. We present in this article the development of our company that uses plastic scintillator for β–particles and thin layer of ZnS(Ag) for α–particles read by SiPM vie wavelength shifting fiber (figure 2c) RZBA–07D [7].

2. Operating principle of the plastic scintillator–WLS–SiPM technology

2.1. Operating principle

In high energy physics there are many tasks that require detectors with large sensitive areas. Common method to get it is the plastic scintillator, wavelength shifting fiber and photodetector (see e.g. [8]). Principle of operation of this technology is as follows (see figure 3):

- Charged particle passed throw the scintillator creates a track of excited molecules.
- Part of the energy is transferred to the scintillating dopant and then to the wavelength shifting dopant that shifts light (black solid line on figure) to the absorption region of a WLS (red dashed line).
- Light is absorbed by the WLS that re–emits it on the green wavelength (green dotted line).
- Emitted light can travel on large distance as the absorption and emission spectrum of WLS are different (i.e. for Kuraray Y11 WLS absorption length to the own light is about 3m). As a result, it is possible to collect light appeared in scintillator from large area.
- End of WLS is connected to a photodetector (blue dashed-dotted line – spectral photon detection efficiency of typical SiPM).

2.2. Silicon Photomultiplier

SiPM is a relatively new semiconductor photodetector that was developed in Russia at the end of 1990th [9]. It consists of a matrix of the independent micro-photodiodes (pixels) on common substrate that connected by aluminium buses and work in Geiger-mode. Each pixel has individual quenching resistor. When a photon enters the depletion region of a pixel the Geiger discharge is developed in it
with some probability – pixel is fired. Number of fired pixels proportional to the intensity of light coming to the detector area. Signals from all fired pixels are summed on the common load. So, output signal is proportional to the light intensity.

Today SiPMs are produced almost everywhere overworld by different companies: Hamamatsu, Ketek, FBK, SensL and others. The quality of detectors is significantly improved and its advantages and drawbacks are revealed by great number of researches [10]. Main features of the SiPM on comparison with PMT can be summarized in table 1.

| Parameter                                      | PMT                                  | SiPM                        |
|-----------------------------------------------|--------------------------------------|-----------------------------|
| Sensitivity                                   | Single photons                       | Single photons              |
| Gain                                          | \( \sim 10^6 \)                       | \( \sim 10^6 \)             |
| Detection efficiency, \%                      | Typical 20–40                         | Typical 35–50               |
| Impulse duration (0,1 level), ns              | 10–100                               | 10–100                      |
| Overall dimensions, mm                        | Min 15x15x5 (MicroPMT)               | 2x3x0.8                     |
| Dark rate, Hz                                 | 1–5 / mm²                            | (50–70) \( \times 10^3 \) / mm² |
| Mechanical robust                             | Medium or low                        | High                        |
| Sensitivity to magnetic field                 | General: Earth field (B \( \sim 50 \) \( \mu \)T) | Very low: no up to 7 T |
|                                              | Metal channel: 5 mT                   |                             |
|                                              | Mesh dynodes: 1.5T                    |                             |
| Temperature sensitivity, \% / °C              | Response \( \sim -1.5 \)              | Response \( \sim -2 \)      |
| Price                                         | \$1000                               | \$20 / mm²                  |

2.3. History of PST-WLS-SiPM technology

That technology (with SiPM usage) in large scale was used at the first time in high energy physics for the Hadron Calorimeter of the International Linear Collider (HCAL ILC). Development of the concept, design and production of the prototype were carried out in the period from 2000 to 2005. It is based on the so called “tile” – a piece of plastic scintillator with embedded WLS fiber, see figure 4a.

Figure 4. First large-scale usage of the SiPM as photodetector for registration of a light from WLS in plastic scintillator. a) different tiles used; b) one layer of hadron calorimeter with area 1 m².
Light from WLS is collected on the SiPM embedded into the tile too. First prototype Minical was built in 2003 and it used tiles with size of 5×5×0.5 cm and consisted of 11 layers each of which contained 9 tiles. After several beam tests at DESY it was proven that SiPM can be successfully used as an alternative for PMT and APD [11,12]. After that the physical prototype was built in 2005 [13]. It had volume 1 m³ and consisted of layers with area 1×1 m² composed from tiles of different sizes for the reason of compromise between cost and granularity, see figure 4a,b. It contained 7608 tiles with SiPMs. This prototype was successfully studied in a series of test beams in the period from 2006 to 2011 in CERN and FNAL.

3. Peculiarities of the tile technology usage in surface contamination monitors

In comparison with high energy physics (HEP) the usage of the tile technology in surface contamination monitors has some peculiarities (see table 2):

| Parameter                           | HEP                                                                 | Radiation monitors                                      |
|-------------------------------------|---------------------------------------------------------------------|--------------------------------------------------------|
| Measurement of the energy deposited in tile | Measured                                                           | No                                                     |
| External trigger                    | Exist                                                               | Absent                                                  |
| Registered particle energy          | > 1 MIP (Minimum Ionizing Particle). In tile with thickness 5 mm it deposits ~1MeV. | Should register presence of nuclides of interest like: $^3$H ($E_{\beta_{\max}} = 0.012$ MeV), $^{14}$C ($E_{\beta_{\max}} = 0.157$ MeV), $^{60}$Co ($E_{\beta_{\max}} = 0.318$ MeV), $^{90}$Sr–$^{90}$Y ($E_{\beta_{\max}} = 2.282$ MeV) |
| Temperature                         | Stabilized about room value                                         | Should work in range from 5 °C to 40 °C                |
| Sensitive area                      | For granularity reasons size of each tile should be as small as possible (last trend: 3×3 cm²) | For uniformity reasons size of the tile should be as large as possible. Sensitive area for foot 15×30 cm² |

4. Choice of the materials and SiPM

From the point of view compromise between quality and cost and based on experience in HEP usage the following materials were chosen after additional R&D research:

- scintillator material is p–terphenyle plus POPOP dissolved in polystyrene. It has light output 30% lower than similar Bicron scintillators but about an order lower cost
- Kuraray Y11 multi cladding WLS fiber

In order to choose SiPM the following requirements were taken into account:

- Dark rate should be as low as possible
- High photon detection efficiency (PDE)
- It should has protection against optical crosstalk (probability that one fired pixel fires another one [14])
- Package that provide mechanical robust.

At the time of R&D research the Hamamatsu MPPC S13360**50PE series in SMD package turned out to be the most suitable and available SiPM. Its parameters are summarized in table 3. On figure 5a photo of the MPPC is presented. Such package is very robust and convenient for embedding into the tile. Spectral sensitivity is well combined with emission spectrum of the Y11 WLS (figure 5b), MPPC has rather short impulse – total duration of about 70ns. Temperature coefficient in table 3 shows how the breakdown voltage changes with temperature.
Figure 5. Hamamatsu MPPC S13360**50PE. a) photo of the MPPC in SMD package; b) comparison of the spectral dependence of the PDE and emission spectrum of the Y11 WLS; c) waveform; d) parameter dependence on overvoltage.

Table 3. Parameters of the Hamamatsu MPPC S13360**50PE.

| Parameter                        | Value                      |
|----------------------------------|----------------------------|
| Gain                             | $2 \times 10^6$            |
| PDE (%)                          | ~45                        |
| Dark rate (0.5 pixel thresh.) (Hz)| $10^5$ (max $2 \times 10^5$) |
| Optical crosstalk (%)            | 5                          |
| Number of pixels                 | 667                        |
| Restoration time (ns)            | ~20                        |
| Breakdown voltage (V)            | 53±5                       |
| Temperature coefficient (V/°C)   | +0.054                     |
| Package                          | SMD, epoxy covered         |

5. Overview of the hand-foot monitor RZBA-07D

Full setup contains three type of modules (see figure 6):

- foot modules with active window $15 \times 31$ cm$^2$ – one module per foot;
- hand modules with active window $12 \times 24$ cm$^2$ – two modules per hand to control both sides at the same time;
- remote module with active window $12 \times 12$ cm$^2$ – for clothes control (it can be made sensitive to $\alpha$-particles using tile from clear plastic with ZnS(Ag) scintillator on surface).

Each module contains tiles with WLS and embedded SiPM, reflecting material from top and bottom of the tile, plate with electronics. Light protection is provided by thin multi-layer aluminized foil. Quick-detachable stainless steel grille provides mechanical protection of the sensitive area, so it is possible to easy change foil if necessary. Correct positions of feet and hands are controlled by 4 sensors for each foot and hand and the warning message appeared on the touch-screen accompanied by a voice in the case of positioning error. To make the control of the hands more ergonomically convenient, blocks for that procedure are fixed at an angle that was determined after a series of tests with people of the different height and build.
6. Module electronics

When we use WLS we deliver only small part of scintillation light to the photodetector and for low energy $\beta$-particles (~100 keV) the signal from it is on the level of several photoelectrons. As MPPC has high dark rate at these thresholds it is necessary to use two detectors in one tile operating in coincidence. So, main measurement path of the module electronics contains: source of bias voltage for MPPC, preamplifier, shaper, discriminator and coincidence unit. In addition, it is possible to measure dark rate of each MPPC directly from discriminator and the rate of delayed coincidences caused by random coincidence of dark impulses from the MPPC. All signals are counted in processor unit. Then the information transmitted to the computer via RS-485 interface. On-plate processor unit controls discriminator thresholds, MPPC bias voltage separately for each detector and trace the temperature via sensor on plate. Temperature variation is compensated by appropriate changing of the MPPC voltage.

Figure 6. Hand-foot surface contamination monitor RZBA–07D a) common view; b) separate modules from bottom to top: foot, hand and remote.

Figure 7. Module electronics. D1, D2 – discriminators; CU – coincidence unit; DCU – delayed coincidence unit; MPU – microprocessor unit. Details see in text.
7. Measurement procedure and results

7.1. Uniformity of the sensitivity on area
For β-modules measurements were made with $^{36}$Cl ($E_{\text{max}} = 0.714$ meV) nuclide point-like source of type OSGI. It is the nuclide medium in the shape of the 4 mm diameter circle spot between thin polyamide films. Module count frequencies were measured in 40, 36 and 25 positions for foot, hand and remote models appropriately (see figure 8a,b,c). The source was positioned so as to get into the hole of the protective grille. Tested area correspond to that described in standard IEC 61098 for foot (10×30 cm) and hand (10×15 cm) modules and in standard IEC 60325 [13] for remote module (area is divided on sections each one having linear dimensions of as near to 25 mm as possible).

For remote α-module measurements were made with $^{239}$Pu nuclide source of type 3P9. It is the nuclide medium in the shape of the circular spot with area 10 cm$^2$ covered with metal oxide film. Module count frequencies were measured in 9 positions (see figure 8d). Maximum difference from mean is in the center and equals -16%.

Results of the measurements for β-modules are presented on figure 9. For foot module frequency differs from average by 14% just at the one corner. If we discard this unique measurement difference from average will not exceed 10%. For hand and remote modules difference from average smaller than 10% and 6% appropriately. In according with standards the variation of response from the mean value with the position of the source shall not exceed a factor of 2.

![Figure 8](image_url) Uniformity of the modules sensitive area. Nuclide source positions. Size of the red circles is greater than source size for visibility. a) foot; b) hand; c) remote β; d) remote α, measured frequency counts and difference from average are shown.

![Figure 9](image_url) Uniformity of the modules sensitive area: a) foot; b) hand; c) remote.

7.2. Energy dependency of the efficiency for β and α particles
Energy dependency of the efficiency for β− and α−particles was measured with the nuclide sources. Measurement procedure was very simple: you just need to divide the measured frequency (with
subtracted background) from the module by the particle surface emission rate of the nuclide source. Results are presented in Table 4.

Table 4. Energy dependence of the efficiency.

| Nuclide | E_{\text{max}}, \text{MeV} | Efficiency, % | Nuclide | E_{\text{mean}}, \text{MeV} | Efficiency, % |
|---------|----------------------------|--------------|---------|---------------------------|--------------|
| 90Sr–90Y | 2.282                      | 72           | 239Pu   | 5.149                     | 40           |
| 204Tl   | 0.763                      | 70           | 234U    | 4.774                     | 35           |
| 14C     | 0.157                      | 10           | 238U    | 4.188                     | 33           |

7.3. Sensitivity to the particle fluence rate

Sensitivity of the module $K$ (Hz·cm$^{-2}$·min$^{-1}$) is defined as ratio of frequency $f$ (Hz) measured by the module to the particle fluence rate $P$ (cm$^{-2}$·min$^{-1}$) and just calculated from the efficiency $\varepsilon$ and module’s active area as follow (assuming that $P = 1$ cm$^{-2}$·min$^{-1}$):

$$K = P \cdot \varepsilon \cdot S / 60$$  \hspace{1cm} (1)

Using this equation, we can get modules sensitivities:

- for $\beta$ (90Sr–90Y): $K_{\text{foot}} = 5.57$ Hz·cm$^{-2}$·min$^{-1}$; $K_{\text{hand}} = 3.45$ Hz·cm$^{-2}$·min$^{-1}$; $K_{\text{remote}} = 2.35$ Hz·cm$^{-2}$·min$^{-1}$
- for $\alpha$ (239Pu): $K_{\text{remote}} = 1.31$ Hz·cm$^{-2}$·min$^{-1}$

7.4. Minimum detectable fluence rate

Minimum detectable fluence rate (cm$^{-2}$·min$^{-1}$) is defined by equation:

$$P_{\text{min}} = \frac{k_0 \sqrt{n_b}}{K \sqrt{t}}$$  \hspace{1cm} (2)

where: $k_0 = k / \delta_P$, $k$ – coverage factor (for an approximate level of confidence of 95%, $k$ is 2); $\delta_P$ – desired measured uncertainty; $n_b$ – background frequency count (Hz); $K$ – module sensitivity (Hz·cm$^{-2}$·min$^{-1}$); $t$ – measurement time (s).

In accordance with standards the control time equals 10 s with $\delta_P = 0.2$. Minimum detectable fluence rate for different modules in comparison with standard’s requirements is presented in Table 5.

Table 5. Minimum detectable fluence rate for different modules in comparison with standard’s requirements.

| Module type     | $n_b$, Hz | Calculation (cm$^{-2}$·min$^{-1}$) | Standard (cm$^{-2}$·min$^{-1}$) |
|-----------------|-----------|----------------------------------|-------------------------------|
| Foot $\beta$    | 50        | 4.0                              | 20                            |
| Hand $\beta$    | 40        | 5.8                              | 10                            |
| Remote $\beta$ (body) | 20     | 6.0                              | 20                            |
| Remote $\alpha$ (body) | <0.01   | 0.2                              | 4                             |

From equation (2) we can calculate the time required to measure any particle fluence rate: if we need to measure $P = 1$ cm$^{-2}$·min$^{-1}$ by hand $\beta$–module with $\delta_P = 0.2$ it will take 330 s. The measurement of the $P = 0.1$ by 1 cm$^{-2}$·min$^{-1}$ by remote $\alpha$–module will take ~60s.

7.5. Dynamic range

Dynamic range measurements of the remote beta– and alpha–modules were made with nuclide sources of type 5S0 (90Sr–90Y) and 5P9 (239Pu) appropriately. Both have active area 100 cm$^2$ in the shape of circular spot. They placed at the center of the module directly on protective grille. Readings from modules in fluence rate units was compared with nominal values provided by sources with accounting for the area difference. The introduction of the correction function on dead time allowed to
significantly increase the dynamic range up $10^6 \text{ cm}^2\text{s}^{-1}$ for $\beta$–module and $2\cdot10^4 \text{ cm}^2\text{s}^{-1}$ for $\alpha$ (see figures 10 and 11):

$$P = P_m \cdot \frac{s_m}{s_0} \cdot \frac{1}{1-f_m t}$$  \hspace{1cm} (3)

where: $P$ and $P_m$ – particle fluence rate after and before correction (cm$^2$s$^{-1}$); $s_m$ and $s_0$ – active area of the module and nuclide source (cm$^2$); $f_m$ – measured frequency (Hz); $t$ – dead time (s).

**Figure 10.** Dynamic range of the remote $\beta$–module.

**Figure 11.** Dynamic range of the remote $\alpha$–module.

### 7.6. Sensitivity of the remote $\alpha$–module to the $\beta$– and $\gamma$–radiation.

To measure sensitivity of the $\alpha$–module to $\gamma$–radiation UPGD-2M-D setup was used changing doze rate in the range 0.0312 mSv·h$^{-1}$ up to 22.9 mSv·h$^{-1}$. The module was installed with a sensitive area to the source. Response of the module to the given doze rate excepted as minimal detectable fluence rate. Background of the remote $\alpha$–module is at the level of $10^{-3}$ Hz and can be neglected. For evaluation of the influence of $\beta$–radiation two nuclide sources $^{90}$Sr–$^{90}$Y with high intensities were used. Source type is 6S0 with area 160 cm$^2$ (10.5×15.5 cm rectangle). Response of the module to the given $\beta$–particle fluence rate excepted as minimal detectable fluence rate. Module showed very low sensitivity to ambient $\beta$– and $\gamma$–radiation (see table 6).

### Table 6. Minimal detectable fluence rate of the remote $\alpha$–module in the presence of ambient $\beta$– and $\gamma$–radiation.

| ambient $\gamma$–radiation | ambient $\beta$–radiation |
|---------------------------|---------------------------|
| Doze rate of $\gamma$ (mSv·h$^{-1}$) | Min. detectable fluence rate of $\alpha$ (cm$^2$·min$^{-1}$) | Fluence rate of $\beta$ (cm$^2$·min$^{-1}$) | Min. detectable fluence rate of $\alpha$ (cm$^2$·min$^{-1}$) |
| < 0.1 | 0.1 | < $10^4$ | 0.1 |
| 0.1 – 5 | 1 | $10^3$ – $10^6$ | 2 |
| 5 – 10 | 10 | | |
7.7. Sensitivity of the hand-foot $\beta$-modules to the $\gamma$-radiation

Hand-foot and remote module sensitive to $\beta$-particles can detect $\gamma$-radiation also. Sensitivity of the remote $\beta$-module was measured to the photons of different energies. The following sources were used:

- $^{60}$Co (E = 1.332 / 1.173 MeV) nuclide setup UPG-D-3K;
- $^{137}$Cs (E = 0.662 MeV) nuclide setup UPGD-2M-D;
- $^{241}$Am (E = 0.059 MeV) nuclide setup UPG-P.

These setups have nuclide of high activity with field calibrated in doze rate units ($\mu$Sv/h) on different distances.

In order to cover the low energy range (60 – 170 keV) more in detail the X-ray tube Isovolt Titan E 225 was used. Doze rate was controlled by universal dosimeter PTW-Unidos E with ionization chamber TN34060-2.5.

Results of the measurements are presented on figure 12. As you can see the module has good sensitivity to $^{137}$Cs of about 420 Hz / ($\mu$Sv/h) but it decreases rapidly for lower energies.

![Figure 12. Sensitivity of the remote $\beta$-module to the $\gamma$-radiation.](image)

Monitor works in the mode of consecutive background compensation. When not in use, the equipment monitors the background from each monitoring channel and stores the information for later subtraction from the measurement signal.

7.8. Sensitivity to the temperature variations

Measurements were made in climatic chamber TX-150 where the temperature was set with accuracy $\pm 2^\circ$ C. Two remote modules, $\beta$- and $\alpha$-sensitive, in full assembly were tested at $+50^\circ$C and $-20^\circ$C.

After temperature reaches the appointed value modules were kept for two hours before measurement.

Table 7. Sensitivity of the RZBA remote module to the temperature variations. Frequency counts at different temperatures.

| Type     | $T = +20^\circ$ C | $T = +50^\circ$ C | $T = -20^\circ$ C |
|----------|------------------|------------------|------------------|
|          | 1 hour | 2 hour | 1 hour | 2 hour | 1 hour | 2 hour |
| $\beta$-module | Source, Hz | 15280 | 15496 | 15550 | 14905 | 14856 |
|          | Background, Hz | 18 | 34 | 44 | 18 | 18 |
|          | Rel. difference (%) | 1.4 | 1.8 | -2.5 | -2.8 |
| $\alpha$-module | Source, Hz | 956 | 928 | 947 | 957 | 953 |
|          | Background, Hz | $< 10^2$ | $< 10^2$ | $< 10^2$ | $< 10^2$ |
|          | Rel. difference (%) | -2.9 | -0.9 | +0.1 | -0.3 |
Used nuclide sources are: $^{90}$Sr–$^{90}$Y for β-particles and $^{239}$Pu for α-particles. Separate measurements of background at temperatures +50 °C and –20 °C were made for β-module. Measured frequency counts are presented in table 7. Equipment demonstrated very good temperature stability: variations of the module response in temperature range from –20 °C up to +50 °C doesn’t exceed 3%.

8. Conclusion
As a result of research and development activity on the NPC “Doza” the new assembly for monitoring the surface contamination of hands, feet and clothing of personnel was developed. Technology “scintillator–WLS–SiPM” had allowed to increase the sensitivity of the hand-foot monitors, reduce the lower edge of energy range, expand dynamic range of the registered fluence rate and decrease the cost. This will ultimately lead to an increase in radiation safety at enterprises that use radioactive materials. Mass production of new equipment has been established.

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