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# Design and development of a plastic scintillator based whole body $\beta/\gamma$ contamination monitoring system

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**Abstract** Plastic scintillation detectors based whole body $\beta/\gamma$ contamination monitors are developed for use in radiation facilities. This microcontroller-based multi-detector system uses 13 plastic scintillator detectors, with minimized dead detection zones, monitoring the whole body, and conforming to the contamination limit prescribed by the regulatory authority. This system has the features for monitoring hands, feet, head, and face $\beta/\gamma$ using contamination monitors and portal exit monitors. It can detect gamma sources at a dose rate of 10 nGyh$^{-1}$. The system is calibrated using $\beta$ sources $^{90}$Sr/$^{90}$Y, $^{204}$Tl, and $^{36}$Cl, and the efficiency is found to be 29%, 22%, and 18%, respectively. The minimum detectable $\beta/\gamma$ contamination is 0.15 Bqcm$^{-2}$, which is significantly less than the minimum detection objectives on head, face, hands, and feet.

**Keywords** Plastic scintillation detector · Contamination monitor · Microcontroller · Minimum Detection Objective (MDO) · Minimum Detection Concentration (MDC)

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## 1 Introduction

Monitoring radioactive contamination on the external body parts of a radiation worker is an integral part of radiological surveillance in a radiation facility. The monitoring technique and system should be adequate to properly assess the occupational radiation safety being maintained and compliance with the requirements of safety directives by regulatory authorities. Contamination monitors are essential for ensuring that the external radioactive contamination levels of an individual are within the regulatory limits. A properly designed contamination monitor is a regulatory requirement that controls radiation exposure, prevents the spread of radioactive contaminations, helps to provide information regarding the regular conditions of the facility, and ensures good working practices. Various types of radiation detectors, such as pancake GM detector, gas flow proportional counters, plastic scintillator and ZnS (Ag) scintillation detectors, are utilized for developing contamination-monitoring systems [1–3]. An alpha surface contamination monitor based on a thick gaseous electron multiplier was proposed by Xiao et al. [4]. Qu et al. [5] reported a new method based on position-sensitive measurements of beta surface contamination, where the detector was a large-area plastic scintillator. The simulation and experimental results provided accurate information of the contamination distribution. Gas flow counter-based contamination monitors require a constant flow of the detector gas medium, and its maintenance is difficult if the entrance window foil ruptures. In the case of gas-flow proportional counters, a constant supply of filled gas at the required pressure must be ensured. Geiger Muller (GM) counter based systems are cheaper; however, despite the use of numerous GM tubes, they suffer from large dead zones, thereby reducing the reliability. NaI (Tl) scintillator detector-based quick scan whole body walkthrough monitors can detect internally deposited gamma-emitting radioisotopes and can be effectively utilized for quick decision making on countermeasures in case of an emergency [6]. An ideal detector used in body contamination monitoring should have a large surface area to cover the body part to be monitored, high beta detection sensitivity of beta energies of $\sim$ 100 keV and above, and good gamma rejection, limiting the minimum detectable activity (MDA). Plastic scintillation detectors for beta and gamma radiation monitoring applications are extensively used mainly because of the easy availability of large-area detectors having the required specifications of shape and size, low price, good sensitivity, and good reliability [7–12]. In addition, they can be easily implemented for operations in rugged fields and require little maintenance.

Occupational workers engaged in radiological operations must be monitored for external beta and gamma contamination and screened according to national regulatory specifications [13]. No transferable contamination on body surfaces is allowed. This entails regular personnel contamination monitoring as per the regulatory stipulations to ensure that no individual carries any radioactive contamination out of the facility. Radiation workers must use radiation monitoring instruments, protective equipment, clothing, and other devices appropriately provided to them to ensure personnel safety. They always use personnel protective wear such as lab coats or specific plant cloths, and the possibility of external $\beta$ contamination on the front and back sides of the body is below average in normal operating conditions. However, the possibility of $\beta$ contamination on other parts such as hands and the sole of shoes cannot be ignored, and it is mandatory to undergo a self-check before leaving the workplace/laboratory. Most of the radioactive materials handled are beta gamma-emitting sources. Despite adequate precautions taken during handling of these sources, there is a possibility of radioactive contamination over the most vulnerable parts such as the hands and feet. Based on the ICRP ALARA principle, exposure of individuals to radiations should be as low as possible, cognizant of social and economic considerations. Therefore, a plastic scintillator detector-based whole body contamination monitoring system is designed and developed. Commercially available plastic scintillation detectors suitable for our application are procured for this purpose. The system is a combination of portal and contamination monitors, comprising cylindrical plastic scintillation detectors (CPDs) and large-area plastic scintillation detectors (LPDs) for the detection of gamma and beta/gamma contamination, respectively. This whole-body contamination monitor proves very effective in the estimation of personnel contamination at radiation facilities where beta/gamma radioactive isotopes are handled. The system is equipped with a user friendly interface and will help individuals to complete a self-check for potential radioactive contamination, thereby limiting the associated radiation risks. The design aspects, development methodology, and characterization results of a body contamination monitor based on plastic scintillation detectors are presented in this paper.

## 2 System design and description

The system comprises 13 plastic scintillator detectors based on combinations of two different shapes and sizes. It uses eight rectangular LPDs (350 mm × 150 mm × 0.5 mm) to monitor $\beta$ and $\gamma$ contamination on the hands, feet, face, and head and five cylindrical CPDs (1000 mm long and a diameter of 51 mm) to monitor $\gamma$ contamination on the front and back sides of the body. Figure 1 shows the system after complete fabrication during testing and evaluation in our laboratory.


**Fig. 1** (Color online) Plastic scintillator detectors based whole body contamination monitoring system

## 3 Detectors

The LPD has a 350 mm × 150 mm × 4 mm light guide and an embedded 2π sensitive photomultiplier tube (PMT) provided with a 100 MΩ resistor divider having a maximum external dimension of 358 mm × 158 mm × 42 mm. It is procured as an integral assembly. The thin plastic scintillator detector has a thickness of 0.5 mm, which ensures the detection of beta particles with excellent gamma rejection.

The detector has an 8.8 mg cm$^{-2}$ entrance window as a reflector and a 20 μm polyamide (Kapton) window for scratch protection. The detector is fitted inside a stainless steel (SS) enclosure tray. Above the Kapton window, an SS honeycomb mesh of 0.1 mm thickness with 90% opening is fitted to the SS tray to protect it from any rough handling during the operation. The entire assembly is wrapped in a polyethylene sheet and placed in another 1 mm thick SS box having a lining of 3 mm lead sheets at the bottom and four sides of the detector for gamma shielding. The LPD has two flying leads RG-174 wires to have high voltage (HV) input and signal output connected to miniature high voltage (MHV) and Bayonet Neill Concelman (BNC) connectors, respectively. The connectors are fitted to a C clamp attached to the SS box. The LPD is light tight and its performance is appropriately tested before it is integrated into the system.

The CPDs are assembled in our laboratory after procuring bare cylindrical plastic scintillators having a length of 1 m and diameter of 51 mm. The plastic detector is wrapped in a thin aluminum foil reflector and coupled to a 51 mm diameter PMT (9266KBS). The detector housing is a 1000 mm long cylindrical polyvinyl chloride (PVC) pipe with one end cap, and the other end is open, where the PMT is coupled to the detector using silica gel. The inner diameter of the PMT enclosure is 52 mm with a screwing arrangement housing to have a light tight assembly. Fourteen pin base B14A socket with divider networks interconnect the PMT and the preamplifier (PA) unit. The detector, PMT and PA are called CPD module and placed in the system with 180° covered (semicircle of backside detector) using a 3 mm lead sheet to provide gamma shielding. The assembled CPD module in our laboratory is rugged for normal handling and requires no further maintenance, and care is taken to make it completely light tight.

## 4 System frame

A SS material is used for the fabrication of the system to have a rigid body, to ensure ease of cleaning and decontamination and help to reduce the gamma background around the detection area. The SS frame has an external physical dimension of 100 cm width, 220 cm height, and 60 cm depth. The frame comprises two feet grill window slots below each installed LPD module. It has two frontal hand monitoring stations with two slots to monitor both hands. Slots are made available at a height of 120 cm with two LPDs facing each other arranged at a gap of 10 cm to monitor beta/gamma hand contamination on either side of the palm. Two infrared (IR) switches are fitted at a depth of 25 cm inside the slots to ensure appropriate positioning of the hands inside the slot. The head and face (HF) monitoring station has two LPDs mounted at right angles to each other. The HF LPDs are mounted on a moving frame to accommodate the likely height variation (150–185 cm) among occupational workers. The HF detectors are mechanically fitted at the top of the SS frame having a sliding pulley arrangement with a counter dead weight balance. The CPDs are arranged within the SS frame such that three detectors are on the backside and two detectors are placed in front to monitor back and chest side of the worker respectively. Perspex sheet (3 mm) covering the inner side of the frame where the person is being monitored. All other sides are covered with 1 mm thick SS sheet. The back CPDs are spaced at a 10 cm gap fixed at a height of 20 cm from the bottom, whereas the two front CPDs are at gap of 5 cm at the same elevation.

## 5 Power supply

The system operates on a 230 V AC, 50 Hz mains supply. A switch mode power supply is used to convert the AC mains to DC levels of ± 12 V and + 5 V, and is placed at the bottom of the back monitoring section of the frame. A 12 V DC is required to operate seven HV modules utilized to power the 13 detectors on a twin sharing basis. The detector processing electronic cards require a DC power supply of ± 12 V and 5 V. The connectors are placed on the power supply distributor cards to energize the respective electronic components of the entire system.

## 6 Processing electronics

Visible light is generated by the interaction of radiations with the detector material. The detector signal is converted to an electrical pulse by the PMT, which is coupled to the detector. The HV of 750 V required for the PMT is generated using commercially available DC to DC converter HV modules. Pulse processing electronics convert the PMT signals into digital pulses. Each detector module is interfaced with the PA, amplifier and discriminator (PAD) electronics to convert detector pulses to transistor-

transistor logic (TTL) output pulses. Figure 2 shows a functional block diagram for processing electronics of the system. The PA, placed near the detectors, provides an interface between the detector and pulse processing electronics.

Its output is fed to an amplifier circuit using operational amplifier integrated circuits (ICs). The amplified pulses are discriminated from noise using a comparator IC. Pulses of amplitude less than 200 mV are rejected for noise discrimination, and the pulses of higher amplitude are further converted to TTL pulses using a monostable multivibrator IC. The typical PAD output TTL pulse width is 5 µs. The PAD cards are placed near the respective detectors, and TTL pulses are fed to the counting electronics through 50 Ω impedance coaxial BNC cables.

Individual detector TTL pulses are counted by a 13 channel counter timer module (CTM) and processed using microcontroller-based control electronics called single-board computer (SBC). The CTM is developed using Philips PCF8583/PCF8593 14 ICs. One of the ICs is used as a real-time clock (RTC) to maintain date/time information, and the rest are used in the event counter mode. Each IC communicates with the SBC using an inter-integrated circuit ($I^2C$) bus on a data pin (SDA) and clock pin (SCL). All the SCL pins of the 14 ICs are tied high with the microcontroller SCL and connected in parallel. Individual RTC/event counter IC SDAs are connected one at a time to the microcontroller SDA through two 8-to-1 decoder ICs (40C51). The selection of the event counter is performed using six select control lines mapped in the data memory. Each detector TTL pulse from the detector is connected to one of the inputs of the AND gate, and other inputs are controlled by the enable/disable signal of the counter from the SBC card. The output of the AND gate is connected to the respective counters.

The SBC is based on Philips 80C552 [14] microcontroller, which is interfaced with a 32 kilo byte (kB) Erasable and Programmable Read Only Memory (EPROM) IC, 32 kB Random Access Memory (RAM) IC, 240 × 128 dots alpha-numeric graphic liquid crystal display (LCD), CTM, audio/visual high alarm indicator, personal scanning mode status indicator switches, RS-232 serial port

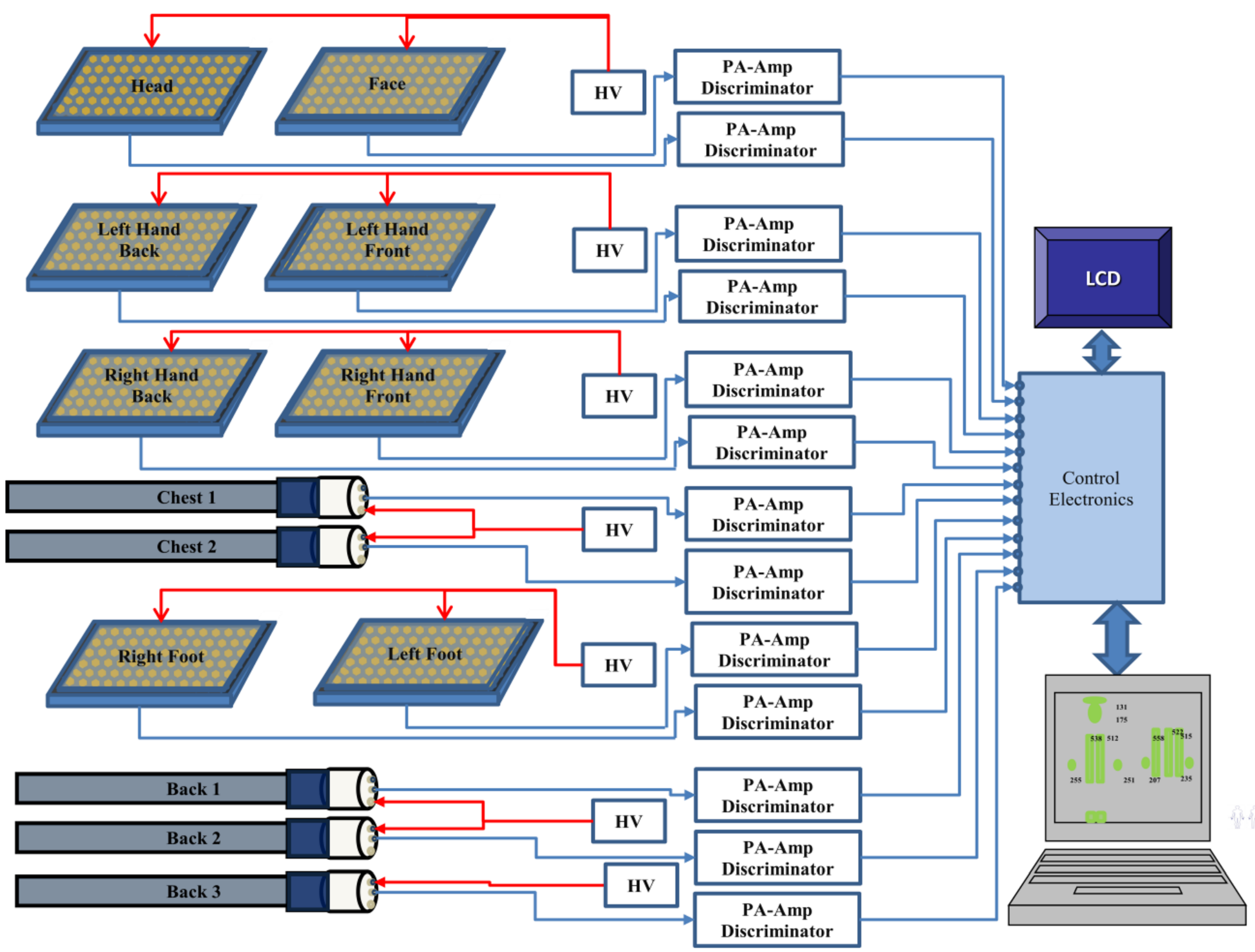


**Fig. 2** (Color online) Block diagram of the processing electronics for the whole body contamination monitoring system

interface, and panel PC, as depicted in Fig. 3. The distinct advantages of microcontroller-based control electronics are their simplicity, low power consumption, failure-proof continuous operation, and operational flexibility.

Using the master (microcontroller) slaves (RTC/event counter ICs) communication protocol, the SBC and CTM communicate with each other through the $I^2C$ bus and interface with each other using a 10 pin flat ribbon cable (FRC). The counters and RTC of the CTM are memory mapped with a microcontroller. The CTM can be controlled sequentially by selecting each successively by the SBC using select control lines, SDA and SCL. The event counter mode includes start, stop counting, and a reading counter. The RTC can be loaded with date/time and read such that data can be logged and stored. The global enable or disable signal from the SBC to the CTM is provided to have the same time slot counting of all detector pulses.

The RAM and RTC have a lithium battery backup for data and RTC date/time retention, respectively, in the case of a power failure. The microcontroller has a watchdog timer, which automatically resets the system if it goes out of synchronization so that it has a 24 × 7 h system operation. The system acquires the detector pulses by CTM for a set acquisition time. If the registered counts exceed the set alarm level, a high alarm is initiated, and the data are stored in the memory with the date and time information in its RAM. The audio-visual alarm module is a self-contained unit designed to provide audio and high visual alarms. The 32 kB data memory is used to save high alarm data with date/time information and system parameters. If a high alarm is not set, the system continues to operate. The SBC is interfaced with personal scanning mode status indicator switches, S1 to S5, to have a close watch on the standing position of the scanned person within the system. S1 and S2 are light sensors that identify whether the monitoring person is positioned properly over the foot detector frames in the system. If the HF monitoring station is properly adjusted, switch S3 is activated. The IR switches, S4 and S5, are activated when the person to be monitored correctly sets their hands in the hand monitoring slots and presses it. A 240 × 128 dot alpha-numeric/graphics LCD (Oriole make model number: OGMY-24011SF) with backlight is used to provide clear visibility even in low ambient light conditions for displaying counts registered by the detectors. The LCD is memory mapped and selected using chip select (CS) and controlled using enable, register select, and eight data lines. The operational functionality of the system is governed by controller electronics with embedded software in the EPROM. The software is developed using the assembly language in a Keil environment. The SBC board is used as a development kit with a program and data memory overlapped in the upper 32 kB address (8000H to FFFF). The embedded monitor program allows hex file to be downloaded in the RAM to be executed for testing. The final tested program is burnt in the EPROM to have a system's operational program.

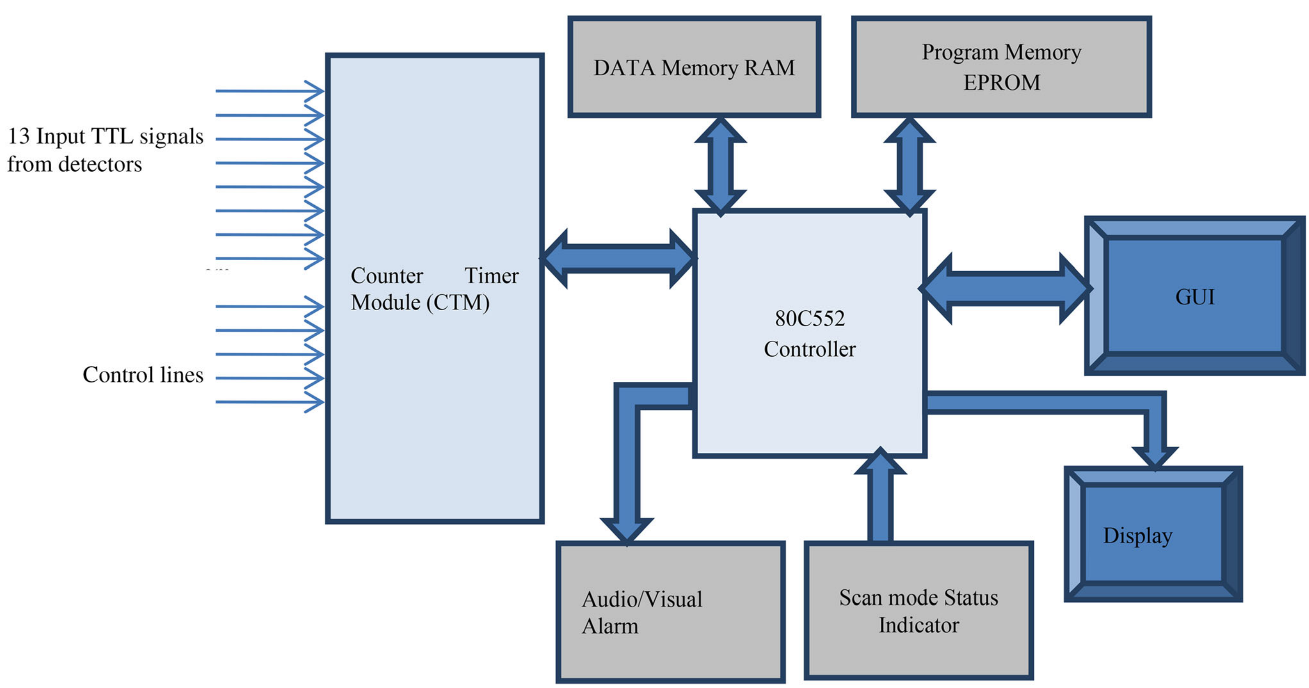


**Fig. 3** Functional block diagram of a microcontroller-based single board computer (SBC)

The system also includes a personal computer (PC) to facilitate data analysis using the graphical user interface (GUI) software. The SBC transfers the acquired detectors counts to the PC in the Windows operating system using a standard serial RS232 protocol. The data are displayed to communicate whether the contamination is more than the permissible level prescribed by the regulatory authority [13].

The design of the system is rugged with SS body and may require very little corrective maintenance. Routine preventive maintenance of the system may include periodic cleaning of the displays and sensors using a soft cloth dampened with only water. The SS frame and lead shielding of the detectors make the system very heavy and fixed at a location.

## 7 Methodology

When the power is ON, the software initializes counters, memory, LCD, and serial interfaces. The system software acquires 13 detector data for the set data acquisition time (1–15 s) continuously to assess the background radiological status of the system located at the workplace. The detector counts are displayed on the LCD and sent to the PC along with the polling status of switches S1 to S5. The situation of uninterrupted switches leads to a background acquisition. This mode of operation is useful for generating baseline background data using various standard sources to ensure proper functionality and setting of the alarm level. It can also be utilized for the periodic evaluation of the efficiency of the system. The background count from each detector when the person is standing on the contamination monitor is less than the earlier registered counts in the absence of the person, which is inferred to be owing to self-shielding effects of individuals and compensated in the personal contamination scanning mode.

When the worker walks in the frame and properly stands on the feet, the IR proximity switches S1 and S2 are interrupted. Thus, the system waits for the scan mode, and instructions are displayed on a PC monitor with audio instruction to pull and properly adjust the HF monitor with face and head, thereby interrupting switch S3 located on the face detector. Once S3 is interrupted, the instruction to place hands correctly into the slots and to press switches S4 and S5 is given. Once all the switches are activated (S1 to S5), the person is asked to wait until the data acquisition is complete. A count down from 10 to 0 is displayed per second. Once the acquisition time is “0”, the instruction to remove hands position back HF monitor module and to leave the monitoring area of the system is given. If the person does not position properly, depending upon the status of the associated switches, an appropriate message is displayed on the PC monitor to follow the instructions. For example, if the left hand switch is not interrupted, a message “insert left hand properly” will be displayed on the monitor after a beep sound. A graphical representation of the radiological status of a human figure is shown. If any of the detectors show higher counts than the set limit for a high alarm, it will be indicated by a green to red color change of the corresponding body part on the human figure and displayed on the monitor. The system captures the photograph and saves, along with data waits for proper countermeasures to be taken by the health physicist. An audio visual high alarm is generated and is ON until the acknowledgment signal is initiated. In a report on high alarm data with RTC timing data, all counts of CPDs converted to dose rate and that from LPDs converted to activity is updated in PC as a pdf file. The data are also displayed on the LCD and stored in the SBC’s memory, which can be retrieved. If the radiological status is normal, then green LED glows and ‘thank you and have a good day’ message with the radiological status on the human figure is displayed.

When the contamination monitor is first powered ON, it takes approximately two minutes to complete the initiation of the system, which also includes the booting of the computer. Subsequently, the system automatically enters into the background count acquisition mode. The system will be ready to monitor any individual worker after the first set of background data is acquired.

## 8 Results and discussions

Eight LPDs and five CPDs were assembled and integrated with the electronics inside the SS frame. The results of the performance evaluation of the detectors and calibration results of the system are described in the following sections. The specifications prescribed by the International Electro-technical Commission (IEC) [15] and similar guidelines by the Bureau of Indian Standards (BIS) [16] for hand and foot contamination monitors have been adopted during the development of this system.

## 9 System performance evaluation

The LPDs are used to assess the $\beta/\gamma$ contamination status of the hands, feet, head, and face of the monitored individual. The combined entrance window thickness of the detector is 20 mg cm$^{-2}$, and the corresponding cutoff $\beta$ particles of energy are less than 100 keV [17]. Experiments were conducted to study the variation in $\beta$ detection efficiency over the surface of the detector and with respect to the source to detector distance.

To estimate the percentage variation of beta detection efficiency over the surface of a large-area plastic scintillator, a study was conducted by recording the efficiency along the length of the detector using a $^{204}$Tl beta source. Figure 4 shows the variation in beta detection efficiency over the surface of the LPD. The scintillator exhibited a slightly lower efficiency at the borders of the detector on both sides. The profile was observed to be slightly asymmetric, and the maximum efficiency was at the center. The efficiency varied between 19.6% at the sides to 22% at the middle along the central line and lengthwise. At the corners of the detector, the efficiency decreased to 17–18%. With gamma-emitting standard sources $^{137}$Cs and $^{60}$Co at the center of the detector, the $\gamma$ response of the LPD was observed to be 400 cps $\mu Gy^{-1}$ $h^{-1}$.

The detector response with the variation of distance between the pure beta-emitting source $^{204}$Tl beta source (742 Bq, endpoint energy 763 keV) was observed. Because the detector response was the maximum at the center, the source was kept at the center and moved away from the center. Figure 5 presents the distance vs. efficiency plot for the $^{204}$Tl beta source. The counting efficiency of the LPD on its surface at distances of 5 mm, 10 mm, 20 mm, 30 mm, and 50 mm at the center of the detector was recorded and plotted. A maximum efficiency of 22% was observed on the surface. It varied from 15 to 4% at distances of 5 and 50 mm. The geometry of the LPD and status indicator switches were arranged such that the source of the contamination (hands, feet, head and face) was not more than 10 cm from the respective detector, for which the efficiency was ~ 13%.

After installing the detectors in the system, the detector performance was evaluated using a $^{204}$Tl source placed on contact at nine points, such as four corners, four center points of surface edges, and a central point. The percentage efficiency variation was ± 10% for all eight detectors.

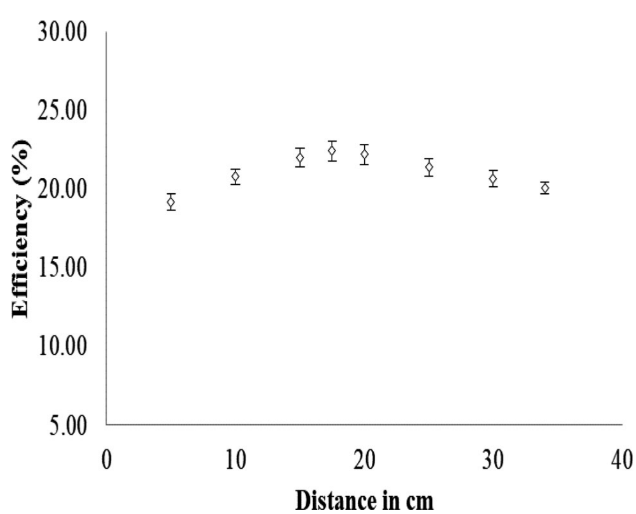


**Fig. 4** Efficiency variation over the surface along the length of LPD

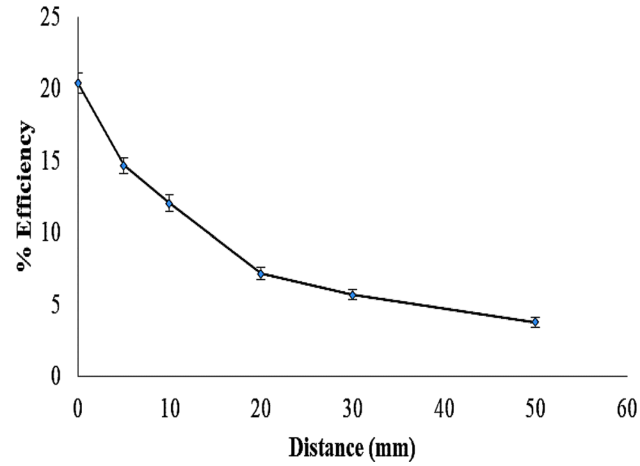


**Fig. 5** Distance versus efficiency plot along the central axis of LPD

The LPD response to the activity variation for the $^{137}$Cs source was performed to determine the linearity in an activity range of approximately 100–2500 Bq. The sources were prepared by depositing known activity on an aluminum planchette using a standard $^{137}$Cs solution.

These sources were kept 3 mm from the center of the detector, and readings in CPS were recorded. The observed CPS versus activity with standard deviation for different standard activity of the source used is shown in Fig. 6. Very good linearity with beta activity response was observed, and the efficiency was 11% with a sensitivity of 0.638 Bq/CPS.

For the detector response evaluation, test point sources were used. In an actual scenario of personnel contamination monitoring, the contaminant source may not be a point source. Therefore, the efficiency variation from the point to the $^{90}$Sr/$^{90}$Y spread-out source (15 cm × 10 cm) was 29% and 33%, respectively, when placed at the center of the detector in contact. The spread-out source was kept at six different locations in three columns and two rows. The efficiency varied from 33 to 35%, and the variation was less than that of the point source when both moved along the surface of the detector.

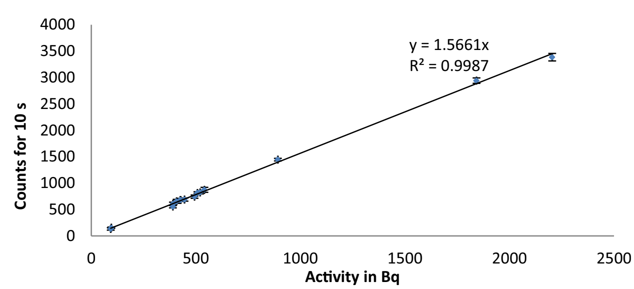


**Fig. 6** LPD response to varying activities of $^{137}$Cs source

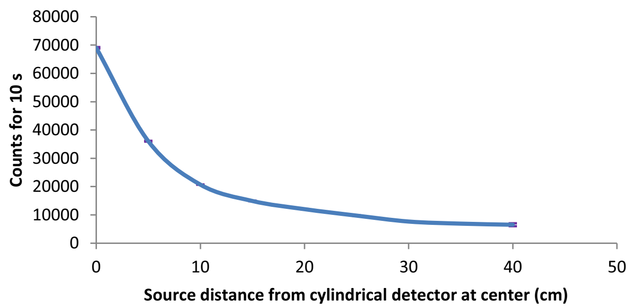


**Fig. 7** Gamma response of CPD for 60 µCi, $^{137}$Cs disk source

The gamma response of the CPD was evaluated using a 60 µCi $^{137}$Cs disk source. The source to detector distance was varied up to 40 cm along the middle of a vertically mounted CPD. Counts were recorded for 10 s. Figure 7 shows a plot of counts (for 10 s) versus the source to detector distance from the center of the detector. At a monitoring distance of approximately 5 cm, the response was 58 cps µCi$^{-1}$.

The count rate variation along the length of the detector was within 10%, and the radial response was nearly uniform. A set of data were recorded to study the dose rate response of the CPD for gamma radiation exposure. Figure 8 shows the linear response of the detector up to 60 µGy h$^{-1}$ with a sensitivity of 1000 cps µGy$^{-1}$ h$^{-1}$, and the pulses turned to saturate beyond a dose rate of 100 µGy h$^{-1}$.

The detector energy response was evaluated using $^{241}$Am, $^{137}$Cs, and $^{60}$Co to cover the energy range of 60 keV to 2 MeV. The response of the detector was independent of the energy, and the variation in the detector response was observed to be within $\pm$ 20%.

The average background counts of the detectors, when tested in our laboratory, were observed as approximately 20 cps for the LPD and approximately 50 cps for the CPD. The data acquisition of the detectors in the background mode was studied after keeping a known $^{137}$Cs test source near the system for a brief period. Figure 9 shows the combined responses of all detectors on the introduction and removal of the test source. In addition, it was observed that the CPDs yielded a higher response than the LPDs conforming to their position and gamma sensitivity.

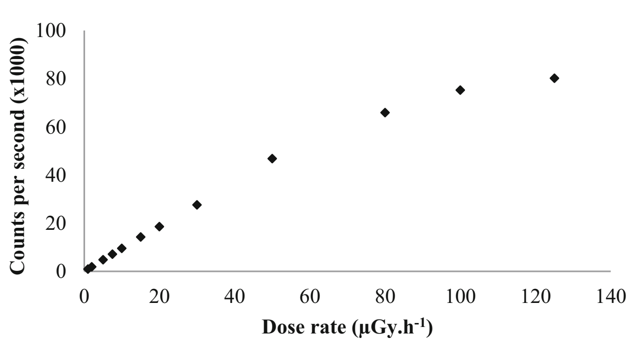


**Fig. 8** Linearity test of CPD for different gamma dose rates

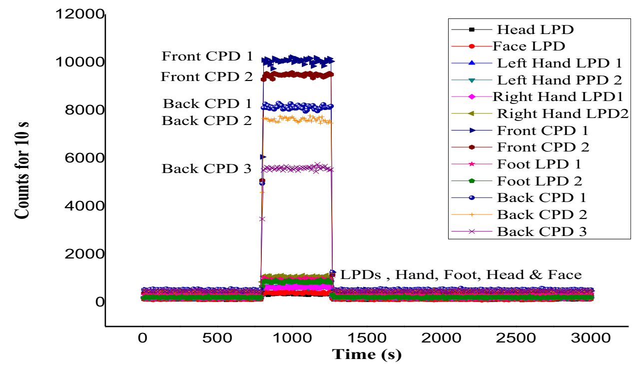


**Fig. 9** (Color online) Responses of the detectors on the introduction and removal of a $\gamma$ source

The detector geometry and their placement were carefully optimized for probable $\beta$, $\gamma$ contamination detection on the hands, feet, head and face. This arrangement was set to ensure minimal dead detection zones in such a system. Five sensors were used to monitor the appropriate positioning of the hands, feet, and face/head of the personnel.

This, in turn, ensured the accuracy of the beta/gamma contamination measurement by the system. Such position sensors are to be incorporated into contamination monitors based on the requirements of IEC standards. Moreover, the main operating system is provided with an uninterruptible power supply. Key features of the contamination-monitoring system are listed in Table 1.

A reduction in recorded counts with respect to the prevailing background counts was observed for all the detectors, whereas non-contaminated personnel stood in the contamination monitor for scanning. The observed reduction in the count rate can be attributed to self-shielding. Human subjects monitored can vary in height from 145 to 185 cm and weight from 45 to 100 kg, so the effect of self-shielding. The average percentage reduction in background counts was maximum for the HF detectors (approximately 12%) and approximately 6% for the hand and foot detectors.

It should be noted that the pair of hand detectors is covered and shielded from all sides except the slot for hand entry, whereas HF detectors are not shielded along one surface. The CPDs showed a reduction of 2–4%. This observation was incorporated into the software to account for the corrected background counts during the process of personnel contamination monitoring.

**Table 1** Key features of whole body contamination monitor

| Sl. no | Feature of the system | | |
|---|---|---|---|
| 1 | Combinational of portal and hand, feet contamination monitor | | |
| 2 | Optimized geometry with multiple detectors for probable $\beta$, $\gamma$ contamination detection on hands, feet, head, and face | | |
| 3 | 13 plastic scintillator detectors, 8 large area scintillator detectors for $\beta$, $\gamma$ measurement, and 5 cylindrical detectors for front and back side $\gamma$ measurement. Detectors are shielded with 3 mm lead | | |
| 4 | Movable head and face detector assembly to take care of 150 cm to 190 cm height variation of monitoring personnel | | |
| 5 | Five sensors to monitor appropriate positioning of hands, feet and face/head of the monitoring personnel | | |
| 6 | Built-in microcontroller and computer manage the system operation and system reliability | | |
| 7 | Minimized dead zones | | |
| 8 | Measurements time 1–15 s | | |
| 9 | LPD efficiencies: | Source | % Efficiency on contact |
| | | $^{137}$Cs | 11 |
| | | $^{36}$Cl | 18 |
| | | $^{204}$Tl | 22 |
| | | $^{90}$Sr/$^{90}$Y | 29 |
| 10 | Gamma source detection sensitivity: 280 Bq of $^{137}$Cs and 76 Bq of $^{60}$Co at 5 cm from the CPD surface for 10-s counting | | |
| 11 | Physical dimension ($w \times h \times d$): 100 cm × 220 cm × 60 cm, Weight: 150 kg | | |

## 10 Calibration and alarm setting of the system

The LPDs were calibrated using standard radioactive disk sources. The efficiencies (on contact) were 29%, 22%, 18%, and 11% for $^{90}$Sr/$^{90}$Y, $^{204}$Tl, $^{36}$Cl and $^{137}$Cs sources, respectively.

The limit of $\beta/\gamma$ fixed contamination, which is the derived working level (DWL) prescribed by the national regulatory authority, is 350 Bq for the hands and 0.37 Bq cm$^{-2}$ for personal shoes, whereas 1.5 Bq cm$^{-2}$ for skin contamination and 2 Bq cm$^{-2}$ for personal clothing [13]. Therefore, our minimum detection objective (MDO) is set by a regulator that is equal to the DWL value. In the case of an average 300 cm$^2$ measurement area of both palms having four LPDs for hand contamination monitoring, the corresponding MDO is 90 Bq. In the case of an average 300 cm$^2$ foot measurement area, the MDO for the detector was assumed to be 100 Bq.

The minimum detection concentration (MDC) values for the system are calculated using the Currie equation given in Eq. (1) [18].

$$N_D = 4.653\sigma_{N_B} + 2.706 \quad (1)$$

where $N_D$ is the minimum number of counts needed from the source to ensure that the false-negative rate is not larger than 5% and $\sigma_{N_B}$ is the square root of the background counts. Equation (2) provides the corresponding MDC value.

$$\mathrm{MDC} = \frac{N_D}{T \times E} \quad (2)$$

where $T$ is the counting time, which is set to 10 s and $E$ is the efficiency of the LPD.

The MDC values were estimated using an average background count rate of 20 cps and an efficiency of 15% at a distance of 5 mm for the $^{204}$Tl β source and found to be 45 Bq for the LPD. The corresponding contamination level was estimated as 0.15 Bq cm$^{-2}$. The minimum detection level (MDL) is less if either the source is in contact with the detector or if the source endpoint energy is greater than 763 keV. Thus, the alarm level can be set anywhere between the MDC and MDO values.

The average background count rate for the CPD was approximately 50 cps. It corresponded to nearly 1000 cps per μGy h$^{-1}$ for a prevalent laboratory background radiation dose rate 50 nGy h$^{-1}$. The MDC for the CPD was also calculated using Eqs. (1) and (2). The $N_D$ value was obtained 11 cps with the Currie equation for the counting time of 10 s. Therefore, the contamination-monitoring system can detect a gamma source with a minimum dose rate of 10 nGy h$^{-1}$, which corresponds to an activity of 280 Bq of $^{137}$Cs and 76 Bq of $^{60}$Co at 5 cm from the CPD surface for a counting duration of 10 s. These activity levels are much below the exemption levels set by international bodies [19]. To identify the inadvertent movement of radioactive sources, an alarm level of 1000 cps was set for the CPDs when counted in the background mode. Generally, this instrument is placed at the exit of the white zone area of a facility where the radiation dose rate should not exceed 1 μGy h$^{-1}$ [13].

## 11 Conclusion

A whole-body $\beta/\gamma$ contamination monitor was developed by employing 13 plastic scintillator detectors. The hands, feet, face, and head were monitored independently using appropriate position sensors as per IEC and BIS standards. The MDC values of the detectors employed in the system were found to be significantly lower than those prescribed by the national regulatory authority. The MDLs for hand and foot contamination detectors (LPDs) for $^{204}$Tl beta-emitting source at 5 mm detector to source distance were found to be 45 Bq and 0.15 Bq•cm$^{-2}$, respectively. This corresponded to 50% and 40% of the respective MDOs. This system is likely to serve as a combination of portal exit and contamination monitors, and it can function as a dual system. Any gamma radiation source movement through the system can be alerted with an MDL of 10 nGy h$^{-1}$. The system is appropriately designed to satisfy the regulatory requirements and will help to complement a series of upstream controls in the facility to ensure radiological safety.

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