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Evaluation of Structural Shielding Designs of X-Ray Linear Accelerator Scanner at the Port of Tema, Ghana

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ABSTRACT

This study was conducted to evaluate the shielding designs of a 6 MeV x-ray linear accelerator scanner used for cargo-container scanning at the port of Tema in Ghana. Workload of the facility had increased significantly over time necessitating review of the installed shielding. There had been introduction of x-ray unit with higher energy (from 5 MeV to 6 MeV) increasing absorbed dose per scan. The number of scans per day had increased from an average of 60 to 95 scans. New structures had been built around the facility without particular attention to their distances and orientations with respect to the radiation source. The principle that the product of the weekly time average dose rates (R_w) and the occupancy for a particular point of interest (location) should not exceed the design dose limit, P (i.e. $P \geq R_wT$) for that location was partly used to determine the adequacy of the shielding afforded by the barriers. In addition to $P \geq R_wT$, calculated and measured hourly time average dose rates (R_h) were used to establish the adequacy of the shieldings based on the dose limit of 0.5µSv/h for public and supervised areas (uncontrolled areas). The R_w, calculated R_h and measured R_h all fell below the dose limit showing that the primary and secondary barriers are adequate.

Keywords: *shielding, dose rate, x-ray, scanner, linear accelerator*

1. INTRODUCTION

There is a worldwide need for effective mass screening of cargo containers at airports, seaports and road border crossings. The main objectives are the detection of contraband such as illicit drugs, explosives, nuclear materials and weapons, and the verification of declared manifests [1]. Most non-intrusive cargo screening systems are based on the use of radiation (X- or gamma-rays).Those systems can provide high-resolution intensity images of the cargo contents and are well suited for detecting metal-based objects such as weapons. The images obtained from the systems are easy to interpret due to the high contrast shapes obtained from the scanning. The most used technologies are based on X- and gamma-rays [2, 3, 4].

The Tema Port in Ghana has a fixed x-ray linear accelerator with energy of 6 MeV for scanning cargo containers. The x-ray linear accelerator scanner is provided with an x-ray emission unit which produces an electron beam after accelerating through energy of 6 MeV [5]. A Radio-frequency (RF) high voltage power supply is applied to the accelerating electrodes. The electron energy, T_n is given by the relation [6]

$$T_n = \frac{1}{2} m v_n^2 = neV \qquad (1)$$

Where V is the accelerating potential, V_n is the electron drift velocity, e is the electronic charge and m is mass of the electron. The length of the accelerating electrodes, L_n corresponding to the electron drift velocity, V_n of about half period of the RF cycle is given by

$$L_n = V_n \frac{T}{2} = T(\frac{neV}{2m})^{(\frac{1}{2})} \qquad (2)$$

where, T is the period of the RF signal.

Due to the harmful effects of ionizing radiation produced by these scanners, shielding designs must be provided to reduce the radiation exposure to acceptable levels. The purpose of radiation shielding is to protect workers and the general public from the harmful effects of ionizing radiation [7].

Shielding should be designed by a qualified expert [8, 9] to ensure that the required degree of radiation protection is achieved [7]. Because any radiation exposure may have an associated level of risk [10], it is important that the qualified expert review the completed facility design to ensure that all anticipated exposures are consistent with the ALARA (as low as reasonably achievable) principle [10, 11].

2. MATERIALS AND METHOD

The x-ray facility, materials and the methods used in conducting the study are described in this section.

2.1 Description of the facility

The fixed x-ray linear accelerator scanner facility operated by the Gateway Services Limited (GSL) was built in December, 2000. It makes use of x-ray source with energy 6 MeV. The dose rate at 1 m is 4 Gy/min (375 rad/min). The single view x-ray scanner has the walls, roof and the floor barriers made of concrete of density 2350 kg.m^{-3}. The shielding door is

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made of steel of density 7800 kg.m^{-3}. The primary and the secondary barriers are made of concrete of thicknesses 1800 mm and 850 mm respectively. It has offices located behind the secondary barrier shielding occupied by staff of the facility which are all designated as supervised (uncontrolled areas).

2.2 Distance measurements on the facility

Distance measurements in metres using surveyor's tape measure were taken as follows: from source-axis of the x-ray scanner to the point behind the primary shielding for primary barrier computations; from source-axis to the points of interest behind the secondary barrier for leakage barrier shielding computations; from the x-ray source to container (scattering surface) for scattered radiation shielding computations; and container to the points of interest for scattered radiation shielding computations.

2.3 Workload Determination

The workload was calculated using equation 3 [7, 8, and 12].

Workload = dose per exposure × no. of exposures/day × no. of working days/week (3)

2.4 Time average dose equivalent rate (TADR) determination beyond primary barrier

Primary barrier: A wall, ceiling, floor or other structure designed to attenuate the useful beam to the required degree [7].

The primary barrier transmission factor expected can be expressed as equation 4 [13].

$$B_e = \frac{1}{10^{t_e/TVL}} \quad (4)$$

where t_e , the thickness of x-ray concrete material employed during construction is 1800 mm; TVL (tenth value layer) for 6 MeV primary x-ray in concrete (density 2350 kg·m^{-3}) is 343 mm [14, 15].

The IDR_p (instantaneous dose rate) in Sv/hr due to the primary beam can be expressed as equation 5 [7, 13].

$$IDR_p = \frac{DR_m 60 B_e}{d^2} \quad (5)$$

DRm, the maximum dose rate output at one metre for the x-ray is 375 rad/min = 4Gy/min; Be is the expected transmission factor; d is the distance from the radiation source to the point to be protected.

The distance d in the above equation is referenced to a distance of 1 m from the source of the radiation. Therefore, due to the inverse square law it is understood that the d^2 value in the equation is divided by (1 m)^2.

The weekly time averaged dose-equivalent rate (R_w) can be expressed as equation 6 [7, 8, 13].

$$R_w = \frac{IDR_p\, W_{pri} U_{pri}}{DR_m} \quad (6)$$

R_w is the TADR averaged over one week (Sv week^{-1})
IDR_p = instantaneous dose-equivalent rate (Sv h^{-1})
DR_m= absorbed-dose output rate at 1 m (Gy h^{-1})
W_{pri} = primary-barrier weekly workload (Gy week^{-1})
U_{pri} = use factor for the location

The maximum dose in-any-hour (TADR) is given by equation 7 [7, 8, 13].

$$R_h = \frac{IDR_p\, W_h U}{DR_m} \quad (7)$$

where DRm is the maximum dose rate output in Gy/hr; R_h is the maximum dose in-any-hour (TADR); W_h is the workload in Gy/hr.

2.5 Time average dose equivalent rate (TADR) determination beyond secondary barrier

Secondary barrier**:** A wall, ceiling, floor or other structure designed to attenuate the leakage and scattered radiations to the required degree [7].

2.5.1 Leakage x-radiation

Leakage radiation: All radiation, except the useful beam, coming from within the accelerator head and other beam-line components. It is attenuated by shielding in the protective source housing as specified by IEC [16].Leakage radiation goes in all directions at roughly the same rate [7].

The expected leakage transmission factors (Bel) can be expressed as equation 8[13].

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$$B_{el} = \frac{1}{10^{t_e/TVL_l}} \qquad (8)$$

where the leakage barrier thickness employed for x-ray is 850 mm; the TVL for 6 MeV x-ray in concrete (density 2350 kg·m^{-3}) for leakage radiation is 279 mm [14, 15].

The instantaneous dose rates (IDR_l) due to leakage is given by equation 9 [13].

$$IDR_l = \frac{DR_m 60 B_{el}/d_{sec}^2}{1000} \qquad (9)$$

where symbols have their usual meanings.

The distance d in the above equation is referenced to a distance of 1 m from the source of the radiation. Therefore, due to the inverse square law it is understood that the d^2 value in the equation is divided by $(1\ m)^2$.

2.5.2 Scattered x-radiation

Scattered radiation: Radiation that, during passage through matter, is changed in direction and the change is usually accompanied by a decrease in energy [7].

The expected container scatter transmission factors (B_{ec}) can be expressed as equation 10[13].

$$B_{ec} = \frac{1}{10^{t_e/TVL_c}} \qquad (10)$$

where t_e, the scatter x-radiation thickness employed is 850 mm; TVL_c, the TVL for 6 MeV x-ray in concrete (density 2350 kg·m^{-3}) for scattered radiation is 171 mm for 90^o scatter [7, 14].

The instantaneous dose rate due to container scatter (IDRc) was determined using equation 11 [13].

$$IDR_c = \frac{DR_m 60 a(\frac{F}{400}) B_{ec}}{d_{sec}^2 d_{sca}^2} \qquad (11)$$

where the symbols have their usual meanings defined earlier in the text.

The distance d in the above equation is referenced to a distance of 1 m from the source of the radiation. Therefore, due to the inverse square law it is understood that the d^2 value in the equation is multiplied by $(1\ m)^2$.

The instantaneous dose rate due to container scatter (IDRc) was determined using equation 12 [13].

$$IDR_c = \frac{DR_m 60 a(\frac{F}{400}) B_{ec}}{d_{sec}^2 d_{sca}^2} \qquad (12)$$

where the symbols have their usual meanings defined earlier in the text.

The distances d in the above equation are referenced to a distance of 1 m from the source of the radiation. Therefore, due to the inverse square law it is understood that the d^2 values in the equation are divided by $(1\ m)^2$.

2.5.3 Total instantaneous dose rates due to leakage and scatter x-and gamma radiation

The total instantaneous dose rates due to leakage and container scatter is given by equation 13 [13].

$$IDR_T = IDR_L + IDR_C \qquad (13)$$

where IDR_L is the instantaneous dose rate due to leakage x-radiation; IDR_C is the instantaneous dose rate due to container scatter x-radiation.

The weekly time averaged dose-equivalent rate (R_w) can be expressed as equation 14 [7, 8, 13].

$$R_w = \frac{IDR_T\, W_{pri} U_{pri}}{D_o} \qquad (14)$$

R_w is the TADR averaged over one week (Sv week^{-1})
IDR_p = instantaneous dose-equivalent rate (Sv h^{-1})
D_o= absorbed-dose output rate at 1 m (Gy h^{-1})
W_{pri} = weekly workload (Gy week^{-1})
U_{pri} = use factor for the location

The maximum dose in-any-hour (TADR) due to leakage and scatter x or gamma radiation can be expressed as equation 15 [7, 8, 13].

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$$R_h = \frac{IDR_T\, W_h U}{DR_m} \qquad (15)$$

where symbols have their usual meanings.

2.6 Evaluation of shielding barriers based calculated and measured dose rates

A Rados model RD-200 universal survey meter calibrated at the Secondary Standard Dosimetry Laboratory(SSDL) of Radiation Protection Institute (RPI) of the Ghana Atomic Energy was used to measure the dose rates at the various points of interest.The measured and calculated dose rates were used to establish the adequacy of the shileding afforded by the primary and secondary barrier.

3. RESULTS AND DISCUSSIONS

Table 1 shows the workloads of the 5 MeV installed previously and the 6 MeV currently in operation. The workload increased from 900 Gy/wk to 1900 Gy/wk with the introduction of the higher x-ray energy of 6 MeV. The increase was as a result of increases in absorbed dose per scan and the number of scans per day and with the number of working days per week unchanged. Workload increases result in increases in the dose rates which may require additional shielding thickness if the maximum dose limit for a particular location is exceeded. So, it is always advisable to review both the primary and secondary shieldings anytime workloads significantly go up.

The weekly time average dose rate (R_w) and the hourly time average dose rate (R_h) beyond primary barrier are shown in Table 2. The R_w and R_h were respectively determined to be 7.36×10^{-6} Sv/wk and 1.84×10^{-7} Sv/hr (0.18 µSv/hr). From Table 4, P > R_wT making the primary shielding acceptable [13, 17]. The calculated R_w of 0.18 µSv/hr (shown in Table 5) and measured dose rates of 0.15 µSv/hr (shown in Table 7) fell below the specified limit of 0.5 µSv/hr [18] for a public areas showing that the primary barrier is adequate.

Table 3 shows the R_w and R_h for the individual points of interest (locations) beyond the secondary barrier. The R_w values were from the least of 2.39×10^{-6} Sv/wk to a maximum of 9.37×10^{-6} Sv/wk and that of the R_h were from 6.12×10^{-8} Sv/hr (0.06 µSv/hr) to 2.34×10^{-7} Sv/hr (0.23 µSv/hr). The R_wT values were found to be less than the designed dose limits for each location (i.e. $R_wT < P$) as shown in Table 4 which are acceptable [13, 17]. Again, the calculated (shown in table 6) and measured R_h (shown in table 7) values for the designated locations beyond the secondary barrier fell below the specified limit of 0.5 µSv/hr [18] for uncontrolled areas(supervised areas) as well as public areas showing that the secondary barrier shielding is adequate.

4. CONCLUSIONS

Theoretical calculations and experimental measurements have been used to assess the adequacy of the shielding afforded by the x-ray linear accelerator scanner at the Port of Tema in Ghana. Important shielding parameters such as designed dose limits (P), workload (W), use factor (U), occupancy (T), maximum dose rate output at 1m (DR_m), distances in metres, thicknesses employed by shielding engineers during construction (t_e) and tenth-value layers(TVL) among others were used in the dose rate computations. The calculated dose rates, measured dose rates and R_wT < P were used to determine the adequacy of the primary and secondary barriers. The R_h values fell below the specified limit of 0.5 µSv/hr for public and supervised areas (uncontrolled areas). Again, the product of the weekly time averaged dose rates (R_w) and occupancies (T) for the various points of interest were all below the designed dose limits (i.e. $R_wT < P$).For the fact that all the above conditions have been fulfilled, the primary and secondary barrier shielding of the scanner are adequate.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation to the Radiation Protection Institute (RPI) of the Ghana Atomic Energy Commission and management of Gateway Services Limited (GSL) for the use of their facilities for this work.

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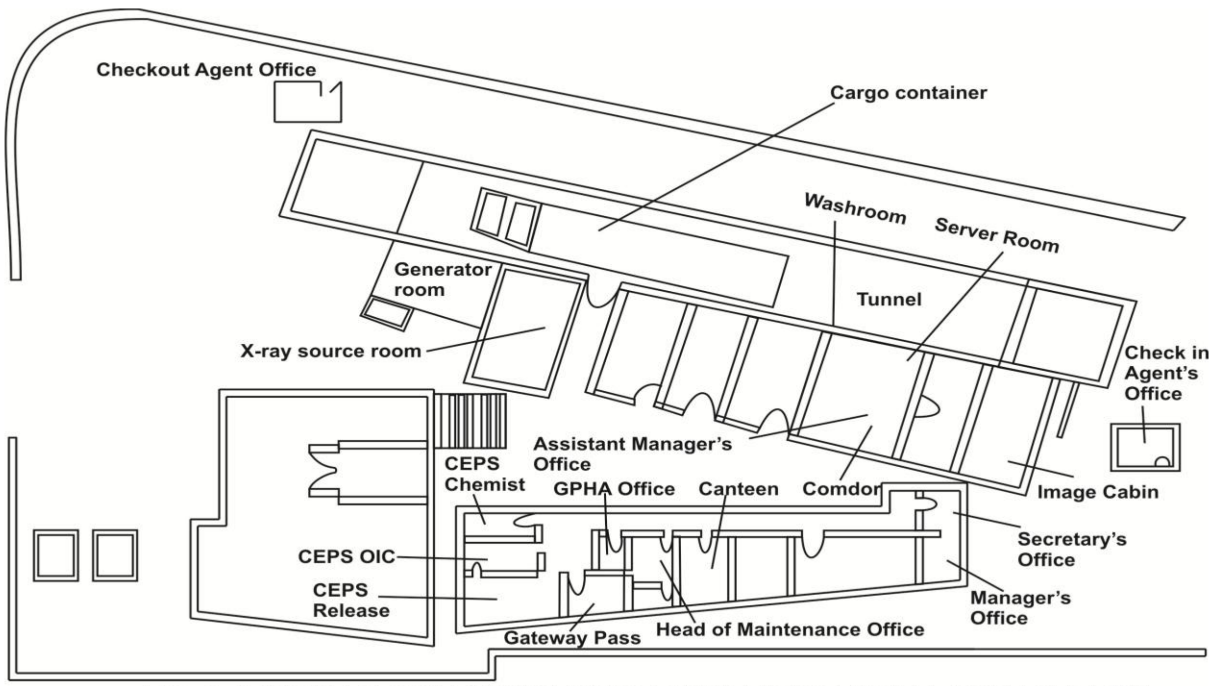

FIG. 1 LAYOUT OF GATEWAY SERVICES LIMITED SCAN SITE, PORT OF TEMA

Volume 3 No.1, January 2013 ISSN 2224-3577

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Table 1: Workload of the X-Ray Scanner

Type of Scanner	Energy (MeV)	Average number of scans/day	Absorbed dose/scan	Number of working days/week	Workload(Gy/wk)
X ray (present)	6	95	4	5	1900
X-ray (past)	5	60	3	5	900

Table 2: Time Average Dose Equivalent Rates (TADR) beyond Primary Barrier

Point of interest	B_e	d(m)	IDR_p(Sv/hr)	R_w(Sv/wk)	R_h(Sv/hr)
Behind detection room	5.65×10^{-6}	19.10	3.72×10^{-6}	7.36×10^{-6}	1.84×10^{-7}

Table 3: Time Average Dose Equivalent Rates (TADR) beyond Secondary Barrier

Point of Interest	d_{sec}	dsca	B_{el}	IDR_L (Sv/hr)	B_{ec}	IDRc (Sv/hr)	IDRL+IDRc (Sv/hr)	Rw (Sv/wk)	R_h (Sv/hr)
secretary's office	14.10	18.90	8.98×10^{-4}	1.08×10^{-6}	1.07×10^{-5}	1.05×10^{-10}	1.08×10^{-6}	8.59×10^{-6}	2.15×10^{-7}
manager's office	21.65	19.80	8.98×10^{-4}	4.60×10^{-7}	1.07×10^{-5}	4.06×10^{-11}	4.60×10^{-7}	3.64×10^{-6}	9.10×10^{-8}
head of maintenance's office	26.70	16.60	8.98×10^{-4}	3.02×10^{-7}	1.07×10^{-5}	3.80×10^{-11}	3.02×10^{-7}	2.39×10^{-6}	5.99×10^{-8}
GPHA office	26.40	20.30	8.98×10^{-4}	3.09×10^{-7}	1.07×10^{-5}	2.60×10^{-11}	3.09×10^{-7}	2.45×10^{-6}	6.12×10^{-8}
gateway pass	13.50	8.80	8.98×10^{-4}	1.18×10^{-6}	1.07×10^{-5}	5.29×10^{-10}	1.18×10^{-6}	9.37×10^{-6}	2.34×10^{-7}
CEPS release	15.10	14.90	8.98×10^{-4}	9.46×10^{-7}	1.07×10^{-5}	1.47×10^{-10}	9.46×10^{-7}	7.49×10^{-6}	1.87×10^{-7}
CEPS OIC	14.10	15.10	8.98×10^{-4}	1.08×10^{-6}	1.07×10^{-5}	1.65×10^{-10}	1.08×10^{-6}	8.56×10^{-6}	2.15×10^{-7}
CEPS chemist	18.40	14.40	8.98×10^{-4}	6.37×10^{-7}	1.07×10^{-5}	1.06×10^{-10}	6.37×10^{-7}	5.04×10^{-6}	1.26×10^{-7}
image cabin	17.50	20.30	8.98×10^{-4}	7.04×10^{-7}	1.07×10^{-5}	5.92×10^{-11}	7.04×10^{-7}	5.57×10^{-6}	1.39×10^{-7}
corridor	15.50	18.10	8.98×10^{-4}	8.97×10^{-7}	1.07×10^{-5}	9.48×10^{-11}	8.97×10^{-7}	7.10×10^{-6}	1.78×10^{-7}
assistant scan manager's office	13.80	13.90	8.98×10^{-4}	1.13×10^{-6}	1.07×10^{-5}	2.02×10^{-10}	1.13×10^{-6}	8.96×10^{-6}	2.24×10^{-7}
Platform (waiting area)	22.80	20.30	8.98×10^{-4}	4.15×10^{-7}	1.07×10^{-5}	3.48×10^{-11}	4.14×10^{-7}	3.28×10^{-6}	8.21×10^{-8}

Table 4: Evaluation of Primary and Secondary Barriers based on weekly TADR

Location	Rw(Sv/wk)	T	RwT(Sv/wk)	P(Sv/wk)	P≥ RwT	**Status**
behind detection room	7.36×10^{-6}	0.06	4.64×10^{-7}	20×10^{-6}	**YES**	**Adequate**
secretary's office	8.59×10^{-6}	1.00	8.59×10^{-6}	20×10^{-6}	**YES**	**Adequate**

Volume 3 No.1, January 2013 ISSN 2224-3577

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manager's office	3.64×10^{-6}	1.00	3.64×10^{-6}	20×10^{-6}	**YES**	**Adequate**
head of maintenance's office	2.39×10^{-6}	1.00	2.39×10^{-6}	20×10^{-6}	**YES**	**Adequate**
GPHA office	2.45×10^{-6}	1.00	2.45×10^{-6}	20×10^{-6}	**YES**	**Adequate**
gateway pass	9.37×10^{-6}	1.00	9.37×10^{-6}	20×10^{-6}	**YES**	**Adequate**
CEPS release	7.49×10^{-6}	1.00	7.49×10^{-6}	20×10^{-6}	**YES**	**Adequate**
CEPS OIC	8.59×10^{-6}	1.00	8.59×10^{-6}	20×10^{-6}	**YES**	**Adequate**
CEPS chemist	5.04×10^{-6}	1.00	5.04×10^{-6}	20×10^{-6}	**YES**	**Adequate**
image cabin	5.57×10^{-6}	1.00	5.57×10^{-6}	20×10^{-6}	**YES**	**Adequate**
corridor	7.10×10^{-6}	0.25	1.78×10^{-6}	20×10^{-6}	**YES**	**Adequate**
assistant scan manager's office	8.96×10^{-6}	1.00	8.96×10^{-6}	20×10^{-6}	**YES**	**Adequate**
platform(waiting area)	3.28×10^{-6}	0.13	4.27×10^{-7}	20×10^{-6}	**YES**	**Adequate**

Table 5: Evaluation of Primary Barrier based on hourly TADR

point of interest	IDRp(Sv/hr)	Rh(Sv/hr)	Rh(μSv/hr)	Limit (μSv/hr)
behind detection room	3.72×10^{-6}	1.84×10^{-7}	0.18	0.50

Table 6: Evaluation Secondary Barrier based on hourly TADR

Location	IDRL(Sv/hr)	IDRc(Sv/hr)	IDRL+IDRc (Sv/hr)	Rh(Sv/hr)	R_h (μSv/hr)	Limit (μSv/hr)
secretary's office	1.08×10^{-6}	1.05×10^{-10}	1.08×10^{-6}	2.15×10^{-7}	0.22	0.50
manager's office	4.60×10^{-7}	4.06×10^{-11}	4.60×10^{-7}	9.10×10^{-8}	0.09	0.50
head of maintenance's office	3.02×10^{-7}	3.80×10^{-11}	3.02×10^{-7}	5.99×10^{-8}	0.06	0.50
GPHA office	3.09×10^{-7}	2.60×10^{-11}	3.09×10^{-7}	6.12×10^{-8}	0.06	0.50
gateway pass	1.18×10^{-6}	5.29×10^{-10}	1.18×10^{-6}	2.34×10^{-7}	0.23	0.50
CEPS release	9.46×10^{-7}	1.47×10^{-10}	9.46×10^{-7}	1.87×10^{-7}	0.19	0.50
CEPS OIC	1.08×10^{-6}	1.65×10^{-10}	1.08×10^{-6}	2.15×10^{-7}	0.22	0.50
CEPS chemist	6.37×10^{-7}	1.06×10^{-10}	6.37×10^{-7}	1.26×10^{-7}	0.23	0.50
image cabin	7.039×10^{-7}	5.92×10^{-11}	7.04×10^{-7}	1.39×10^{-7}	0.14	0.50
corridor	8.97×10^{-7}	9.48×10^{-11}	8.97×10^{-7}	1.78×10^{-7}	0.18	0.50
assistant scan manager's office	1.13×10^{-6}	2.02×10^{-10}	1.13×10^{-6}	2.24×10^{-7}	0.22	0.50
platform(waiting)	4.15×10^{-7}	3.48×10^{-11}	4.15×10^{-7}	8.21×10^{-8}	0.08	0.50

 ISSN 2224-3577

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Table 7: Calculated and Measured hourly TADR

Location	Calculated dose rates(Sv/hr)	Calculated dose rates(μSv/hr)	Measured dose rates(μSv/hr)	Limit (μSv/hr)
behind detection room	1.84×10^{-7}	0.18	0.15	0.50
secretary's office	2.15×10^{-7}	0.22	0.25	0.50
manager's office	9.10×10^{-8}	0.09	0.10	0.50
head of maintenance's office	5.99×10^{-8}	0.06	0.05	0.50
GPHA office	6.12×10^{-8}	0.06	0.08	0.50
gateway pass	2.34×10^{-7}	0.23	0.20	0.50
CEPS release	1.87×10^{-7}	0.19	0.20	0.50
CEPS OIC	2.15×10^{-7}	0.22	0.19	0.50
CEPS chemist	1.26×10^{-7}	0.23	0.25	0.50
image cabin	1.39×10^{-7}	0.14	0.12	0.50
Corridor	1.78×10^{-7}	0.18	0.19	0.50
assistant scan manager's office	2.24×10^{-7}	0.22	0.25	0.50
platform(waiting area)	8.21×10^{-8}	0.08	0.06	0.50