Technical Paper https://doi.org/10.7733/jnfcwt.2023.028

Evaluation of Occupational, Facility and Environmental Radiological Data From the Centralized Radioactive Waste Management Facility in Accra, Ghana

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(Received February 20, 2023 / Revised April 19, 2023 / Approved July 6, 2023)

Evaluating the effectiveness of the radiation protection measures deployed at the Centralized Radioactive Waste Management Facility in Ghana is pivotal to guaranteeing the safety of personnel, public and the environment, thus the need for this study. Radiagem™ 2000 was used in measuring the dose rate of the facility whilst the personal radiation exposure of the personnel from 2011 to 2022 was measured from the thermoluminescent dosimeter badges using Harshaw 6600 Plus Automated TLD Reader. The decay store containing scrap metals from dismantled disused sealed radioactive sources (DSRS), and low-level wastes measured the highest dose rate of $1.06 \pm 0.92\ \mu Sv \cdot h^{-1}$. The range of the mean annual average personnel dose equivalent is 0.41–2.07 mSv. The annual effective doses are below the ICRP limit of 20 mSv. From the multivariate principal component analysis biplot, all the personal dose equivalent formed a cluster, and the cluster is mostly influenced by the radiological data from the outer wall surface of the facility where no DSRS are stored. The personal dose equivalents are not primarily due to the radiation exposures of staff during operations with DSRS at the facility but can be attributed to environmental radiation, thus the current radiation protection measures at the Facility can be deemed as effective.

Keywords: Radioactive waste, Disused sealed radioactive sources, Multivariate analysis, Principal component analysis, Radiological data, Thermoluminescent dosimeter

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1. Introduction

The Radioactive Waste Management Centre (RWMC) of the Radiation Protection Institute (RPI), Ghana Atomic Energy Commission (GAEC) receives radioactive wastes mostly as disused sealed radioactive sources (DSRS) from various clients, then characterizes, treats, packs, conditions and stores the waste at the Centralized Radioactive Waste Management Facility (CRWMF) for future disposal. Therefore, the RWMC is responsible for the safe and secure management of all radioactive waste generated in Ghana from various sectors of the economy such as industry, medical facilities, universities, mining, and road construction. The ultimate aim of radioactive waste management is to handle and manage all generated radioactive waste using sustainable approach that protects the environment and human health, now and in the future, devoid of imposing unnecessary burden on present and future generations [1]. The management practices adopted by the RWMC ensure that the population and the environment are satisfactorily protected, now and into the future. However, the attainment of this noble aim comes with attendant radiation exposures to the occupationally exposed persons (OEP) consisting of scientists, radiation safety officers, and technologists at the RWMC.

The RWMC since its establishment in July 1995 [2] has received more than three hundred (300) DSRS generated from industrial, medical and research applications. These sources cumulatively account for circa 55 TBq activity at the CRWMF. The radioactive waste management activities undertaken at CRWMF include off-loading, characterization of the DSRS, transfer of sources into the storage units, updating of the inventory and all other predisposal activities such as dismantling of devices and removal of bare sources for conditioning. The facility has a large area for receipt, characterization and dismantling of DSRS, and that is labelled as the holding area (HA). There are two main storage units for radioactive waste; area for high dose store (HDS) where high activity DSRS are stored, and decay store (DS) where low activity wastes pending clearance are stored. The storage units, therefore, host conditioned and unconditioned DSRS pending disposal. The conditioning of retrieved sources from dismantled radioactive devices is performed at Office 3 (OFF-3) of the facility.

At the core of effective radioactive waste management is the safety of the OEP. In this regard, as low as reasonably achievable (ALARA) principle is strictly observed to limit the exposure of individuals to acceptable levels of radiation. A radiation protection programme has been instituted and implemented by the RPI which includes workplace and personnel radiation surveillance. The facility has been designated as a radiologically controlled area, thus staff of the RWMC working in the facility are designated as OEP. Therefore, the OEP is provided with the necessary training, personal protective equipment (PPE) and thermoluminescent dosimeters (TLD) badges for personal radiation dose monitoring. The radiation protection program of the RWMC integrates both international recommendations and the radiological safety requirements of the Ghana Nuclear Regulatory Authority (NRA). Dose constraints established by the International Commission on Radiological Protection (ICRP) ensures that exposures of individuals within the workplace are justifiable and acceptable [3]. The occupational radiation dose is expressed by the ICRP in terms of equivalent dose and effective dose. Equivalent dose refers to the dose received by the lens of the eyes, skin, and extremities, whilst effective dose implies the dose received by the whole body. The annual effective dose limit specified by the ICRP is twenty (20) mSv, with a five-year limit of one hundred (100) mSv, however, the dose should not exceed 50 mSv in any single year. The equivalent dose limit of skin and extremities is 500 mSv, and 200 mSv for the eye lenses [4-6].

According to the International Atomic Energy Agency's (IAEA) basic safety standards (BSS), the personal dose equivalent, depicted by the operational quantity, Hp(10) is the recommended international operational parameter in individual monitoring radiation protection program. Hp(10) refers to the dose received by tissue (effective dose) at a 10

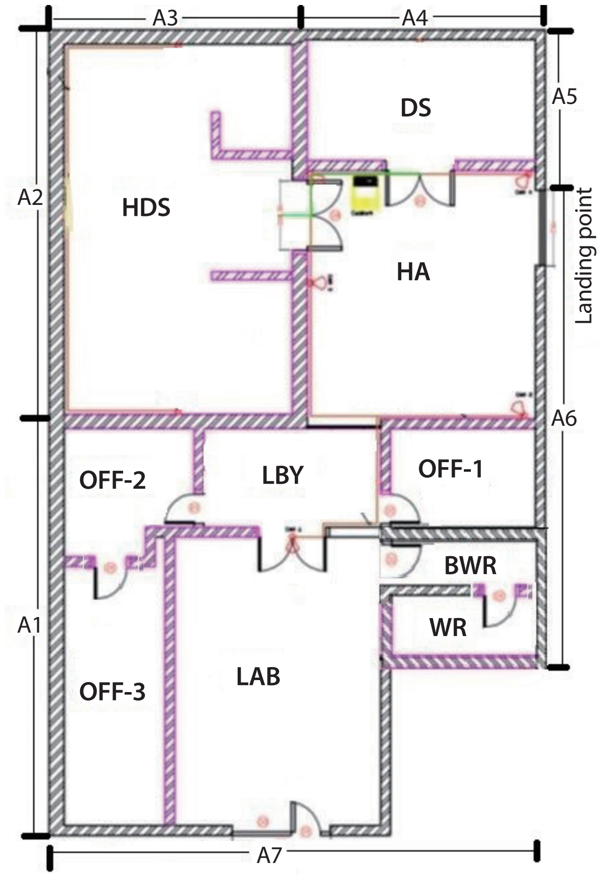

Fig. 1. Floor plan of the Centralized Radioactive Waste Management Facility (CRWMF); the description of various units is shown in Table 1.

Table 1. Description of various locations in and around the CRWMF

Label	Description
HDS	high dose store where sealed radioactive sources (SRS) are stored
DS	decay store where low level wastes pending decay clearance, and scrap metals from dismantled DSRS are stored
HA	holding area; large area for receipt, characterization and dismantling of DSRS
LAB	Laboratory where radioactive waste processing and treatment will occur in the future
LBY	lobby area serves an integral area for defense in-depth
OFF-1	Office 1 where conference desk is located with bookshelves
OFF-2	Office 1 where site investigatory and other equipment are kept
OFF-3	Office 3 where hot cell for DSRS conditioning is established
BWR	washroom lobby
WR	washroom
A1	outer wall surface of OFF-2 and OFF-3
A2	outer wall surface of HDS adjacent to A1
A3	outer wall surface of HDS adjacent to A4
A4	outer wall surface DS adjacent to A3
A5	outer wall surface of DS adjacent to A6
A6	outer wall surface of HA, OFF-1, BWR and WR adjacent to A5
A7	outer wall surface of OFF-3, LAB and WR

mm depth from the skin surface. It is considered as the dose to the whole body (that is the total effective dose) since internal radiation exposure via the intake of radionuclides at the facility is assumed to be negligible. The CRWMF handles and manages only sealed radioactive sources with no reported occurrence of surface contamination or airborne radionuclide contamination. In this regard, the estimation of committed effective dose from internal exposure was deem inapplicable in this study. The dose to the extremities of the body is assessed via the operational quantity Hp(0.07) which is defined as the dose at a 0.07 mm depth within the skin. It is representative of the dose received by the skin of the OEP. Dose estimation for OEP is essential in evaluating radiation risks and the establishment of relevant protective measures [7]. In this regard, this study evaluates the individual annual dose records of OEP at the RWMC in relation to the radiation levels in and around the CRWMF from 2011–2022. This study will, therefore, facilitate the assessment of the effectiveness of the existing radiation protection program established by the RPI in Ghana with reference to the recommended ICRP dose limits.

2. Materials and Methods

2.1 Radiation Dose Rate Measurement in and Around the CRWMF

The ambient dose equivalent rate at various locations in

Fig. 2. Radiagem™ 2000 personal portable dose rate and survey meter.

and around the CRWMF (see Fig. 1 and Table 1) was surveyed/monitored monthly using a calibrated Radiagem™ 2000 personal portable dose rate and survey meter (see Fig. 2). The unit of measurements was $\mu Sv \cdot h^{-1}$, and the recorded monthly values were then used to estimate the annual average dose rates for each location. Background dose rate measurements were conducted fifty (50) metres away from A7 (50-A7) where no radioactive materials are kept. However, the background values were not subtracted from the measurements recorded from other locations of the facility as shown in the results and discussion section due to the negligible values obtained.

2.2 Occupational Radiation Dose Measurement

Thermoluminescent dosimetry is considered as one of most effective approaches for measuring personal exposure to radiation [7]. A retrospective analysis was undertaken on the effective radiation doses for OEP working at the CRWMF in Ghana for a period of 12 years (2011–2022). The external radiation exposure of each OEP is regularly monitored by means of thermoluminescent dosimeter (TLD) badges. The badge is normally worn at the waist level whenever the personnel are working in and around the CRWMF. The TLDs are subsequently sent at quarterly intervals to the Personal Dosimetry Laboratory (PDL) of the RPI for measurement and analysis. The PDL utilizes LiF-100 TL dosimetry system for the measurement and analysis. In this regard, the Harshaw 6600 Plus Automated TLD Reader, a state-of-the-art dosimetry system for whole body, neutron, extremities, and environmental monitoring is used [8]. Two personal dose equivalent values, Hp(0.07) and Hp(10) are quantified and recorded for each personnel. Background dose levels from previous routine monitoring activities using control dosimeters were negligible, thus, background deduction was not applied to the personnel doses in this study. Further information on the measurement, analysis, and calibration of the TLD badges can be found in Al-Abdulsalam and Brindhaban [3] and Hasford, Owusu-Banahene [8].

2.3 Data Analysis

The radiological data from the CRWMF and RWMC OEP covering a period of twelve (12) years were retrieved and transferred to Microsoft excel for univariate and multivariate statistical analysis. Principal component analysis (PCA) multivariate technique was used to reduce the complexities in data, to ascertain the patterns and clusters in the radiological data thereby maximizing the latent information in the research data. PCA essentially reduces a complex data set with multiple variables by transforming the data into a new data set such that fewer new orthogonal variables known as principal components (PCs) are achieved. As indicated in equations 1 to 3, the PCs are linear combination of the initial variables (X_i) (that is the radiation dose rates and personnel dose equivalents) by which various coefficients ($b_{i\,j}$) of the terms in the equation promotes minimal correlation among the new variables [9-12]. Where *n* refers

Table 2. Radiological data from the Centralized Radioactive Waste Management Facility

Year	Radiation measurement, $\mu Sv \cdot h^{-1}$														
	A1	10-A1	A2	10-A2	A3	10-A3	A4	10-A4	A5	10-A5	A6	10-A6	A7	10-A7	50-A7
2011	0.12	0.15	0.13	0.13	0.12	0.15	0.12	0.14	0.12	0.13	0.12	0.13	0.30	0.25	0.27
2012	0.21	0.26	0.20	0.29	0.25	0.43	0.24	0.36	0.22	0.25	0.21	0.27	0.16	0.26	0.33
2013	0.14	0.20	0.21	0.21	0.22	0.31	0.20	0.27	0.19	0.23	0.14	0.22	0.16	0.34	0.26
2014	0.14	0.20	0.18	0.24	0.25	0.38	0.21	0.36	0.19	0.24	0.18	0.20	0.19	0.33	0.23
2015	0.08	0.12	0.09	0.10	0.15	0.20	0.11	0.18	0.12	0.13	0.09	0.12	0.09	0.17	0.13
2016	0.03	0.04	0.04	0.04	0.06	0.07	0.03	0.06	0.04	0.05	0.03	0.04	0.03	0.07	0.04
2017	0.07	0.10	0.08	0.09	0.15	0.13	0.09	0.12	0.10	0.12	0.06	0.10	0.06	0.15	0.08
2018	0.06	0.09	0.08	0.12	0.29	0.14	0.09	0.18	0.06	0.13	0.05	0.09	0.05	0.14	0.06
2019	0.05	0.10	0.06	0.10	0.36	0.19	0.08	0.13	0.06	0.09	0.06	0.07	0.05	0.15	0.07
2020	0.06	0.09	0.10	0.09	0.38	0.12	0.08	0.11	0.08	0.12	0.05	0.08	0.05	0.13	0.08
2021	0.06	0.08	0.08	0.10	0.73	0.17	0.24	0.13	0.08	0.13	0.05	0.08	0.05	0.20	0.11
2022	0.09	0.11	0.08	0.12	0.75	0.17	0.09	0.16	0.09	0.16	0.06	0.12	0.06	0.20	0.11
Mean ± SD	0.09 ± 0.05	0.13 ± 0.06	0.11 ± 0.06	0.14 ± 0.07	0.31 ± 0.22	0.20 ± 0.11	0.13 ± 0.07	0.18 ± 0.10	0.11 ± 0.06	0.15 ± 0.06	0.09 ± 0.06	0.13 ± 0.07	0.10 ± 0.08	0.20 ± 0.08	0.15 ± 0.10

Year	Radiation measurement, $\mu Sv \cdot h^{-1}$									Personal dose equivalent, mSv						
	DS	HA	LBY	LAB	OFF-3	OFF-2	OFF-1	BWR	WR	Hp (0.07)	Hp (0.07)−	Hp (0.07)+	Hp (10)	Hp (10)−	Hp (10)+	No. of person
2011	0.25	0.20	0.07	0.10	0.07	0.10	0.09	0.06	0.08	1.17	0.85	1.74	1.53	1.05	1.98	8
2012	3.84	0.34	0.15	0.15	0.14	0.15	0.20	0.15	0.15	1.17	0.53	1.89	1.40	0.58	2.52	10
2013	0.77	0.21	0.11	0.14	0.14	0.14	0.11	0.12	0.14	2.07	0.87	2.95	2.47	0.93	3.4	13
2014	0.87	0.28	0.12	0.13	0.15	0.17	0.32	0.14	0.13	1.52	0.23	2.33	1.27	0.30	1.99	13
2015	0.73	0.34	0.09	0.06	0.07	0.06	0.06	0.06	0.04	0.85	0.39	1.14	1.01	0.60	1.24	11
2016	0.38	0.09	0.01	0.02	0.02	0.02	0.01	0.01	0.01	1.62	0.28	2.26	2.11	0.34	3.4	7
2017	0.92	0.15	0.04	0.05	0.05	0.05	0.04	0.05	0.04	1.19	0.41	1.82	1.34	0.47	2.07	8
2018	0.95	0.26	0.04	0.05	0.04	0.05	0.04	0.05	0.06	1.19	0.41	1.82	1.34	0.47	2.07	8
2019	1.01	0.19	0.03	0.06	0.06	0.05	0.04	0.05	0.04	2.18	0.45	3.06	2.24	0.46	3	8
2020	1.07	0.17	0.03	0.05	0.04	0.06	0.04	0.04	0.04	0.32	0.19	0.44	0.39	0.15	0.51	9
2021	0.67	0.23	0.05	0.04	0.05	0.06	0.04	0.04	0.04	0.51	0.14	1.18	0.54	0.2	1.35	9
2022	1.25	0.29	0.06	0.10	0.07	0.09	0.07	0.06	0.06	0.46	0.12	1.18	0.49	0.13	1.35	7
Mean ± SD	1.06 ± 0.92	0.23 ± 0.08	0.07 ± 0.04	0.08 ± 0.04	0.07 ± 0.04	0.08 ± 0.05	0.09 ± 0.09	0.07 ± 0.04	0.07 ± 0.05	1.19 ± 0.60	0.41 ± 0.25	1.82 ± 0.77	1.34 ± 0.68	0.47 ± 0.29	2.07 ± 0.89	

As shown in Fig. 1, A1 refers to the outer wall surface of Office 2 (OFF-2) and Office 3 (OFF-3) where the radiation was monitored; A2 refers to the outer wall surface of high dose store (HDS) adjacent to A1 where the radiation was monitored; A3 refers to the outer wall surface of HDS adjacent to A4 where the radiation was monitored; A4 refers to the outer wall surface decay store (DS) adjacent to A3 where the radiation was monitored; A5 refers to the outer wall surface of DS adjacent to A6 where the radiation was monitored; A6 refers to the outer wall surface of holding area (HA) , Office 1 (OFF-1), washroom lobby (BWR) and washroom (WR) adjacent to A5 where the radiation was monitored; A7 refers to the outer wall surface of Office 3 (OFF-3), laboratory (LAB) and WR where the radiation was monitored; whilst LBY refers to the lobby area. The prefixes 10 or 50 before any of these labels refers to radiation been monitored from 10 m or 50 m distance, respectively from the wall surface. **Note that 50-A7 represents the background radiation dose rate.** Hp(0.07), Hp(0.07)-, and Hp(0.07)+ refer to the annual average personal dose equivalent at a depth of 0.07 mm on the body, the minimum measured value of Hp(0.07), and maximum measured value of Hp(0.07), respectfully whilst Hp(10), Hp(10)-, and Hp(10)+ refer to annual average personal dose equivalent at a depth of 10 mm on the body, the minimum measured value of Hp(10), and maximum measured value of Hp(10), respectively. SD refers to the standard deviation.

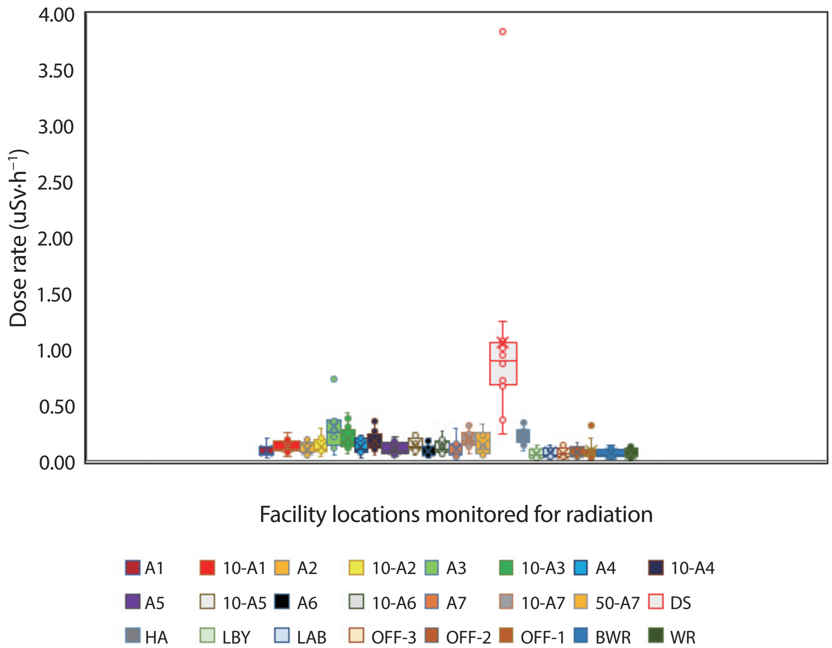

Fig. 3. Variations in the dose rates at various locations of the radioactive waste storage facility.

to the total number of original and new variables. The reduction in the number of variables and complexity in the original data is achieved by selecting useful PCs based on a descending trend of contribution to the total variance in the data set such that PC1 contributes higher variance than PC2, and likewise PC2 than PC3 etc [12].

$$PC_1 = b_{1\,1}X_1 + b_{1\,2}X_2 + b_{1\,3}X_3 + \cdots + b_{1\,n}X_n \quad (1)$$

$$PC_2 = b_{2\,1}X_1 + b_{2\,2}X_2 + b_{2\,3}X_3 + \cdots + b_{2\,n}X_n \quad (2)$$

$$PC_n = b_{n\,1}X_1 + b_{n\,2}X_2 + b_{n\,3}X_3 + \cdots + b_{n\,n}X_n \quad (3)$$

The application of statistical analysis is therefore, envisaged at producing valuable information that will contribute to the safe and effective management of radioactive waste in Ghana. Microsoft Excel with StatistiXL add-in statistical software tools were used in this study. The knowledge gained from this study will be beneficial to other countries especially those with less established radioactive waste management infrastructure thereby ensuring that both staff and the environment are effectively protected during the management of radioactive waste.

3. Results and Discussions

3.1 Univariate Evaluation of Radiological Data

The range for the generated mean annual average radiological data from 2011 to 2022 for both inside and around the CRWMF is 0.07–1.06 $\mu Sv \cdot h^{-1}$ compared to 0.46–0.57 $\mu Sv \cdot h^{-1}$ reported by Pereira, Kelecom [13] at a low activity radioactive waste storage facility in Brazil. The minimum estimate of 0.07 $\mu Sv \cdot h^{-1}$ was recorded at the lobby area, office 3, washroom lobby and washroom areas. These four areas with minimal dose rates tantamount to background measurement are not used for storing DSRS even though OFF-3 is occasionally used for conditioning of sources. Therefore, it can be inferred that the conditioning processes

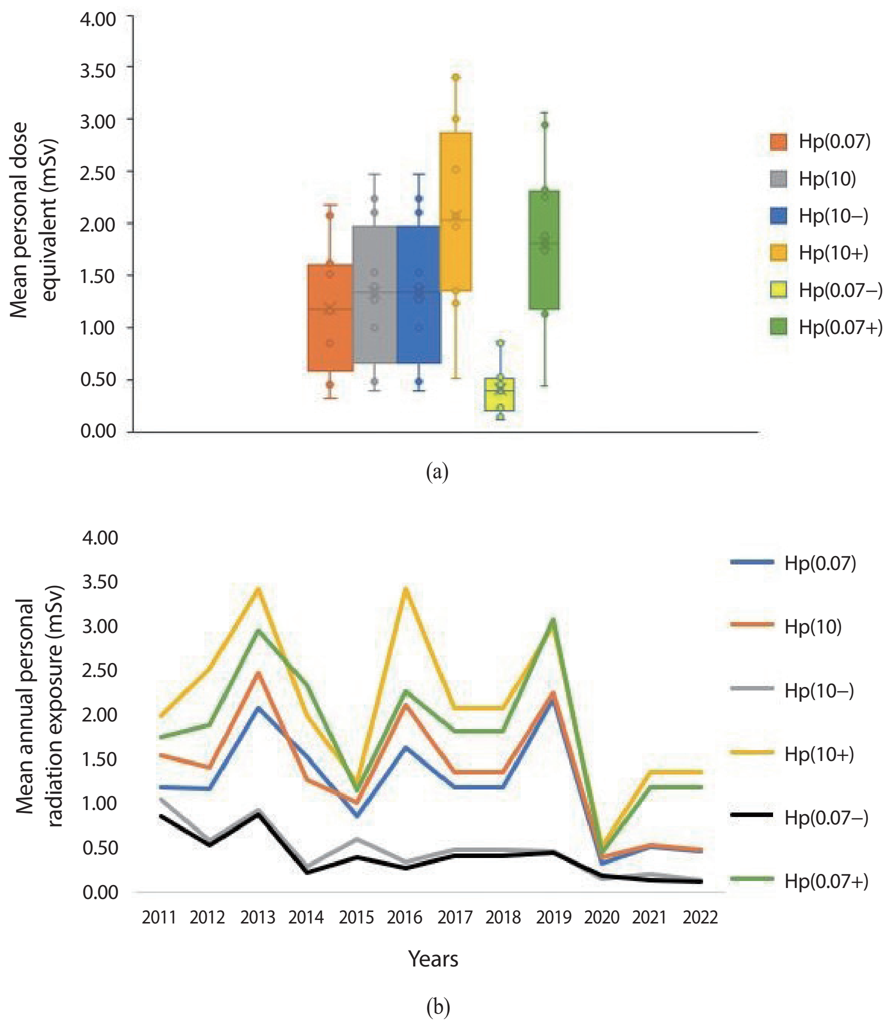

Fig. 4. Variations in the mean annual average personal dose equivalent.

leave behind no potential contamination. The data further shows that the Decay Store recorded the highest mean annual radiation dose rate of 1.06 ± 0.92 $\mu Sv \cdot h^{-1}$ followed by A3 and HA with dose rates of 0.31 ± 0.22 and 0.23 ± 0.08 $\mu Sv \cdot h^{-1}$, respectively (see Table 2 and Fig. 3). The DS contains scrap metals from dismantled DSRS, and very low-level wastes (see Table 1) such as hand gloves and discarded laboratory apparels produced from the operations of Ghana's Research Reactor. The highest annual average radiological value of 3.84 $\mu Sv \cdot h^{-1}$ which was measured at DS in 2012 can be attributed to the temporary storage of the DSRS at this area when the facility was under renovation in 2012. The sources were subsequently relocated permanently to the HDS area upon completion of the facility modernization process, hence the decrease in the dose rate for ensuing years in the DS area.

A3 refers to the outer wall surface of the High Dose Store where category 1 and 2 DSRS are stored. According to the IAEA [14], category 1 DSRS refer to radioactive materials that can cause permanent injury to an individual who comes into contact with the material for over a few minutes if it is not securely protected or managed. Therefore,

Table 3. Explained variance/eigenvalues

Value	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Eigenvalue	19.818	5.028	1.839	1.090	0.763	0.521
% of Var.	66.061	16.760	6.129	3.634	2.542	1.738
Cum. %	66.061	82.821	88.949	92.583	95.125	96.864

Table 4. Component loadings of the initial variables to the principal components

Variable	PC 1	PC 2	PC 3	PC 4	Variable	PC 1	PC 2	PC 3	PC 4
A1	0.971	0.090	0.078	−0.144	DS	0.547	0.309	−0.331	−0.641
10-A1	0.986	0.021	0.004	−0.118	HA	0.572	0.524	−0.012	−0.216
A2	0.952	−0.023	0.133	0.053	LBY	0.959	0.110	0.057	−0.088
10-A2	0.976	0.104	−0.137	−0.075	LAB	0.962	0.042	0.018	0.072
A3	−0.144	0.687	−0.234	0.361	OFF-3	0.970	0.033	−0.099	0.125
10-A3	0.952	0.100	−0.252	−0.047	OFF-2	0.954	0.113	0.023	0.225
A4	0.775	0.255	−0.093	0.210	OFF-1	0.847	0.155	−0.165	0.213
10-A4	0.950	0.131	−0.200	−0.007	BWR	0.985	0.044	−0.121	−0.028
A5	0.975	0.028	0.055	−0.047	WR	0.973	−0.015	−0.039	0.055
10-A5	0.954	0.216	−0.064	0.052	Hp(0.07)	0.277	−0.871	−0.355	0.101
A6	0.977	−0.008	0.065	−0.089	Hp(10)	0.210	−0.947	−0.222	−0.031
10-A6	0.979	0.064	−0.027	−0.128	Hp(10)−	0.444	−0.654	0.548	−0.130
A7	0.703	−0.219	0.571	0.182	Hp(10)+	0.224	−0.845	−0.402	−0.047
10-A7	0.906	0.016	0.128	0.378	Hp(0.07)−	0.470	−0.691	0.455	−0.129
50-A7	0.931	−0.061	0.277	−0.050	Hp(0.07)+	0.335	−0.800	−0.433	0.175

contact with quantities of this unshielded material for a duration of approximately minutes to an hour can result in fatalities. On the other hand, exposure to unshielded quantities of categories 2 and 3 DSRS can lead to fatalities within hours to days, and days to weeks, respectively [15]. The measured dose rate of A3 is not alarming primarily due to the effectiveness of the thick concrete walls in shielding the associated radiation emanating from the category 1 and 2 sources. HA is one of the key areas of the facility for the receipt, characterization and dismantling of DSRS whenever the need arises. The levels of radiation dose rate across all other segments and surroundings of the facility are generally very low and similar in distribution across the twelve-year monitoring period (see Fig. 3). It must be noted that the dose rate at the high dose store was not measured since there was no significant justification in line with the application of the ALARA principle. Moreover, there is lack of a remote radiation monitor within the HDS to enable the remote measurement of dose rates.

The range of the mean annual average personnel dose equivalent data is 0.41–2.07 mSv (see Table 2). Hp(10)+ was the highest estimate (2.07 ± 0.89 mSv) followed by Hp(0.07)+ (1.82 ± 0.77 mSv) whilst the least estimate was recorded by Hp(0.07)−(0.41 ± 0.25 mSv) (see Fig. 4(a) and Table 2). A comparison of the occupational radiation exposure data from this study with the ICRP limits indicates that

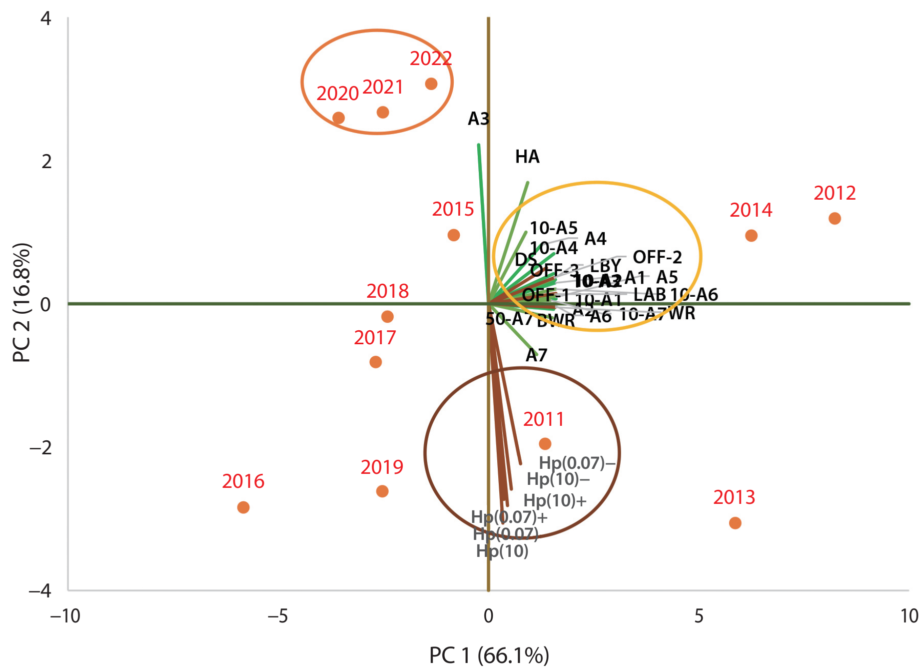

Fig. 5. Biplot of PC1 and PC2.

all the measured values were extremely low. This implies that all the current radiation protection measures deployed by the RWMC in the management of radioactive waste in Ghana is effective in protecting the health of the OEP and by extension the public.

A comparison of the different categories of annual average personnel dose equivalent data as displayed in Fig. 4(b) shows similar distribution pattern between Hp(0.07)− and Hp(10)−, Hp(0.07) and Hp(10), and Hp(0.07)+ and Hp(10)+. This observation shows that similar results may be obtained when personal radiation exposure is estimated at 0.07 mm and 10 mm depth from the skin surface. To further explore the latent patterns between the various parameters, the radiological data was subjected to multivariate analysis below.

3.2 Multivariate Evaluation of Radiological Data

A data matrix consisting of 12 objects and 30 variables was subjected to principal component analysis. As shown in Table 2, the 12 objects represent the different years for which the 30 radiation dose rate and personnel dose equivalent variables were measured. The data was pre-processed using standardization due to the differences in units and variance of variables. The result of the analysis shows that four (4) principal components (PC) were found to be significant based on Eigenvalues > 1 (see Table 3) and they cumulatively accounted for 92.5% variance in the data. However, the loading contributions of most of the original variables to PC1 and PC2 are very high compared to PC3 and PC4 (see Table 4). Moreover, PC1 and PC1 accounted for 82.8% variance in the data. In this regard, only the biplot between PC1 and PC2 as shown in Fig. 5 is considered in this discussion.

The radiological data for most of the areas monitored formed one cluster on the positive axis of PC1 except A3, HA and A7 as shown in Fig. 5, and this cluster was influenced by 2012 and 2014 radiation monitoring data. A3 and HA have more variance in their associated data and with reference to Fig. 5, they could be considered as a cluster. As already noted from the univariate analysis, these two areas measured the second and third highest mean annual average radiological data. A3 and HA are mostly influenced by the annual average radiological data from 2015, 2020 to 2022. The radiological data from 2020 to 2022 can be described as similar due to the cluster formed in Fig. 5. The biplot shows that all the personal dose equivalent clustered together and this further confirmed earlier observations made under the univariate discussion whereby similar distribution patterns were observed between Hp(0.07)− and Hp(10)−, Hp(0.07) and Hp(10), and Hp(0.07)+ and Hp(10)+. The cluster of the dose equivalent is mostly influenced by the radiological data from A7 due to the positive correlation between these variables as shown in Fig. 5. It must be noted that A7 is the outer wall surface of OFF-3, LAB and WR where no DSRS are stored. In this context, the personal dose equivalent estimates obtained and utilized in this study may not necessarily be attributable to the radiation exposures of staff during their operations at various sections of the CRWMF where the DSRS are stored. As a result, the personnel exposure at the facility is essentially due to environmental radiation. Moreover, since all the estimated dose equivalent values are below regulatory threshold it may be inferred that all the current radiation protection measures deployed by the RWMC during the management of radioactive waste in Ghana are effective in guaranteeing the health and safety of the OEP and the environment.

4. Conclusions

This study assessed the radiological data gathered from the management of radioactive waste facility in Ghana covering a period of twelve (12) years from 2011 to 2022. Radiagem^{TM} 2000 was used in measuring the dose rate in and around the Centralized Radioactive Waste Management Facility (CRWMF). The personal radiation exposure to the occupationally exposed persons (OEP) at the CRWMF was estimated from the thermoluminescent dosimeter (TLD) badges assigned to the OEP using Harshaw 6600 Plus Automated TLD Reader. The data was subjected to univariate and principal component analysis (PCA) multivariate analysis. The results showed that the range for the mean annual average radiological data from CRWMF was 0.07–1.06 μSv·h^{-1}. The minimum estimate of 0.07 μSv·h^{-1} was recorded at the office 3, lobby area, washroom lobby and washroom areas where no DSRS are stored. Decay store (DS) recorded the highest mean annual radiation dose rate of 1.06 ± 0.92 μSv·h^{-1} and contains scrap metals from dismantled DSRS, and very low-level wastes such as hand gloves and discarded laboratory apparel from the operation of Ghana's Research Reactor. The range of the mean annual average personnel dose equivalent data was 0.41–2.07 mSv. The estimated annual effective doses from the present study were below the International Commission on Radiological Protection (ICRP) limit of 20 mSv. The PCA biplot showed that all the personal dose equivalent clustered together with high correlation between Hp(0.07)− and Hp(10)−, Hp(0.07) and Hp(10), and Hp(0.07)+ and Hp(10)+. The cluster of the dose equivalent was mostly influenced by the radiological data from A7 where no DSRS are stored. In this context, the personal dose equivalent measurements used in the present study cannot be scientifically ascribed to the radiation exposures of staff during their regular operations at the CRWMF where DSRS are stored. Secondly, since the dose equivalents of personnel are extremely lower than the regulatory limit, it may be deduced that the current radiation protection measures deployed by the RWMC in the management of radioactive waste in Ghana are effective in guaranteeing the health and safety of the OEP as well as the environment.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgements

The authors are most grateful to the Radiation Protection Institute (RPI) of the Ghana Atomic Energy Commission (GAEC) for availing all the needed facilities to conduct this study. We acknowledge the tremendous support extended to us by Edith Amoatey and Edward Gyasi of the External Dosimetry Laboratory at RPI, GAEC.

REFERENCES

[1] M.I. Ojovan and W.E. Lee, "Principles of Nuclear Waste Management", in: An Introduction to Nuclear Waste Immobilisation, 2nd ed., 65-74, Elsevier, UK (2014).

[2] E.T. Gloverand and J.J. Fletcher, "Safe Management of Radioactive Waste in Ghana", International Conference on the Safety of Radioactive Waste Management, IAEA-CN-78/81, 321-324, IAEA, Cordoba, Spain (2000).

[3] A. Al-Abdulsalam and A. Brindhaban, "Occupational Radiation Exposure Among the Staff of Departments of Nuclear Medicine and Diagnostic Radiology in Kuwait", Med. Princ. Pract., 23(2), 129-133 (2014).

[4] N. Shubayr, Y. Alashban, M. Almalki, S. Aldawood, and A. Aldosari, "Occupational Radiation Exposure Among Diagnostic Radiology Workers in the Saudi Ministry of Health Hospitals and Medical Centers: A Five-year National Retrospective Study", J. King Saud Univ. Sci., 33(1), 102149 (2021).

[5] International Commission on Radiological Protection, The 2007 Recommendations of the the International Commission on Radiological Protection, ICRP Publication 103, Ann. ICRP, 37(2-4), 1-4, Elsevier, UK (2007).

[6] International Commission on Radiological Protection, General Principles for the Protection of Workers, ICRP Publication 75, Ann. ICRP, 27(1), 1-7, Elsevier, UK (1997).

[7] M.H. Nassef and A.A. Kinsara, "Occupational Radiation Dose for Medical Workers at a University Hospital", J. Taibah Univ. Sci., 11(6), 1259-1266 (2017).

[8] F. Hasford, J. Owusu-Banahene, J.K. Amoako, F. Otoo, E.O. Darko, G. Emi-Reynolds, J. Yeboah, C.C. Arwui, and S. Adu, "Assessment of Annual Whole-body Occupational Radiation Exposure in Education, Research and Industrial Sectors in Ghana (2000-09)", Radiat. Prot. Dosimetry, 150(3), 350-358 (2012).

[9] G. Gbeddy, A. Goonetilleke, G.A. Ayoko, and P. Egodawatta, "Application of Multivariate Data Techniques in Photochemical Study of Polycyclic Aromatic Hydrocarbons (PAHs) and Transformed PAH Products in Road Dust", Ecotoxicol. Environ. Saf., 196, 110478 (2020).

[10] J.H. Kim, R.H. Kim, J. Lee, T.J. Cheong, B.W. Yum, and H.W. Chang, "Multivariate Statistical Analysis to Identify the Major Factors Governing Groundwater Quality in the Coastal Area of Kimje, South Korea", Hydrol. Process., 19(6), 1261-1276 (2005).

[11] G.K. Gbeddy, "Transformation and Degradation of Organic Pollutants on Urban Road Surfaces", in School of Civil and Environmental Engineering, Queensland University of Technology: Queensland, Australia, 340 (2020).

[12] J.N. Miller and J.C. Miller, Statistics and Chemometrics for Analytical Chemistry, 6th ed., Pearson Education Limited, England (2010).

[13] W.S. Pereira, A. Kelecom, F.S. Cunha, and A.X. Silva, "Occupational Monitoring at Radioactive Waste Deposit", 2017 International Nuclear Atlantic Conference-INAC 2017, Associação Brasileira de Energia Nuclear-ABEN: Belo Horizonte, MG, Brazil (2017).

[14] International Atomic Energy Agency, Categorization of Radioactive Sources, IAEA Safety Standard Series, Safety Guide, No. RS-G-1.9 (2005).

[15] U.S. Department of Energy. March 19 2004. "Environment, Safety and Health Reporting Manual." U.S. DOE homepage. Accessed Feb. 05 2023. Available from: https://www.directives.doe.gov/directives-documents/200-series/0231.1-DManual-1ac2.