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Research Article

Public Health Effects of Radioactive Airborne Effluents from Nuclear and Coal-Fired Power Plant

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It has been well known that nuclear power plant and coal-fired power plant release some amount of radioactive materials during their normal operations. The purpose of this study was to compare radiation exposure doses to the public as a consequence of airborne effluents released from nuclear and coal-fired power plants under the normal operation. NRCDose3 was used to estimate radiation exposure doses to the public from gaseous effluents of nuclear power plant during its normal operation while CAP88-PC was used to calculate doses to the public living around coal-fired power plant. The results showed that radiation exposure doses from nuclear power plant were less than those from coal-fired power plant and regulatory annual limits. Effective dose by external exposure, skin equivalent dose, and organ equivalent dose from gaseous effluents of nuclear power plant were 2.93×10^{-4} mSv/y, 2.90×10^{-3} mSv/y, and 1.78×10^{-2} mSv/y, respectively. On the contrary, the corresponding effective dose by external exposure, external skin dose, and organ dose from coal-fired power plant were 1.13×10^{-2} mSv/y, 5.33×10^{-2} mSv/y, and 1.17×10^{-1} mSv/y, respectively.

1. Introduction

As the world's population increase, the demand for all resources, particularly energy for electricity production, is expected to increase. This means combustion of coal will increase since coal is a dominant source of electricity among traditional combustion energy sources. The contribution of coal in the energy mix as of 2019 was 38 % of total electricity in the world [1]. However, various issues such as health and climate change arise as consequences of burning of coal. Coal-fired power plant is one of the contributors of air pollutant and toxic elements such as sulfur dioxide, nitric oxide, and residual carbon [2]. The coal-fired power plant releases a small amount of radioactive gaseous effluents to the environment [3]. This is because the coal contains naturally occurring radioactive materials such as uranium, thorium, and their daughter products. On the contrary, nuclear energy is a reliable source for electricity production and carbon-free energy source. It is also one of significant solutions for the replacement of traditional combustion energy sources to solve energy and environmental challenges. However, under the normal operation, there is a small amount of radioactive materials discharged to the environment in the form of gas and liquid from the nuclear power plant [4]. The coal-fired power plant is a dominant energy source of electricity production in Mongolia. Its contribution in energy mix as year of 2018 was 73 % of total electricity production. Currently, there are ten coal-fired power plants in operation in Mongolia. The coal-fired power plants and burning of coal in households are the main contributors to air pollution in Ulaanbaatar, the capital city of Mongolia [5]. Air pollution is a challenging issue in Mongolia, particularly in the extremely cold winter season. The concentration of PM 2.5 in the air reaches the highest value of 200 μg/m^3 on January as a consequence of burning coal, as shown in Figure 1 [6]. The reason is that outside temperature drops up to -30°C in January demanding a high amount of coal to produce electricity and heat.

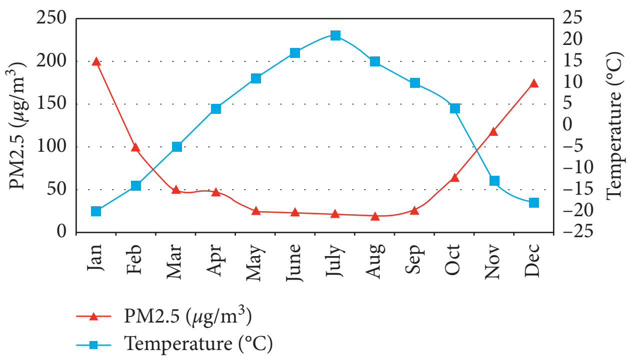

Figure 1: Monthly variation of PM 2.5 levels and temperatures.

Figure 1 shows a monthly variation of PM 2.5 levels and temperatures of Ulaanbaatar city. According to the World Health Organization (WHO), air pollution is one of the environmental risks to human health. It is also the major factor that increases the burden of disease from heart disease, lung cancer, stroke, and so on. According to the study conducted by United Nations International Children's Emergency Fund (UNICEF), people living in Ulaanbaatar city have a high risk of getting a disease related to the lung than those who live in outside of the city. In Mongolia, the mortality rate caused by air pollution was 132 deaths per 100,000 capita as the year of 2018. Also, 40% of lung cancer deaths were due to air pollution in the Ulaanbaatar [7]. To address this issue, nuclear and renewable energy referred to in energy and infrastructure sector of policy document which, namely, "Sustainable development vision 2030" approved by Mongolian parliament. One of the objectives of the energy and infrastructure sector in Mongolia is to ensure stable and reliable supply of energy domestically. To achieve this objective, the government has set three implementation phases. Phase I is to meet up to 85 percentage and phase II and phase III are to meet up to 90 percentage and 100 percentage of the national demand, respectively. Another objective is to increase the share of renewable energy and to seek new energy sources. To accomplish this second objective, the government has specified three implementation phases. The first phase is to increase the share of renewable energy up to 20 percentage and initiate the preparation for a nuclear power program. The second phase is to increase the share of renewable energy up to 25 percentage and complete the preparation for a nuclear program. The third phase is to increase the share of renewable energy up to 30 percentage and commence the nuclear program [8].

2. Materials and Methods

NRCDose3 was used to estimate radiation doses to individuals (adult, teen, child, and infant), and it consists of three programs such as XOQDOQ, GASPAR, and LADTAP [9]. XOQDOQ and GASPAR have been used in this study. XOQDOQ is the atmospheric dispersion model and is designed for evaluating routine releases from NPP. It calculates annual effluent concentrations X/Q values and annual deposition D/Q values. These values are computed 22 specific distances out to 80 km from the nuclear power plant. Meteorological data is as a joint frequency table, i.e., a table of the fractional occurrence during a given time period of a particular combination of stability class type, wind direction, and wind speed class. Wind directions are classified into 16 sectors proceeding clockwise from N to NNW. The wind speed is grouped into 9 classes, which include a class for calm wind speeds. Atmospheric stability is grouped into seven categories from extremely unstable to extremely stable [10]. The plume concentration depleted by dry deposition and radioactive decay. The concentration value X/Q is calculated by the following formula:

$$\frac{X}{Q}(x,K)=\frac{2.032}{x}RF(x,K)\sum_{i,j}^{N,7}\frac{DEPL_{ij}(x,K)\mathrm{DEC}_i(x)f_{ij}(K)}{\overline{U}_i(x)\sigma_{zj}(x)}\exp-0.5\left(\frac{h_e^2}{\sigma_{zj}(x)^2}\right), \tag{1}$$

where $X/Q(x,K)$ = effluent concentration at x in direction K, x = downwind distance (meters), i = the ith wind speed class, j = the jth atmospheric stability class, K = kth wind-direction sector, $\overline{U}_i$ = midpoint value of the ith wind speed class, $\sigma_{zj}(x)$ = the vertical plume spread for stability class j at distance x, $f_{ij}(K)$ = joint probability of occurrence of the ith wind speed class for jth stability class and kth wind-direction sector, h_e = effective plume height, $\mathrm{DEC}_i(x)$ = decrease due to radioactive decay at distance x for the ith wind speed class, $\mathrm{DEPL}_{ij}(x,K)$ = decrease due to plume depletion at distance x for the ith wind speed class, jth stability class, and kth wind-direction sector, and $\mathrm{RF}(x,K)$ = correction factor for recirculation and stagnation at distance x and kth wind-direction sector.

Deposition values D/Q per directional sector is computed using the following formula:

$$\frac{\overline{D}}{Q}(x,K)=\frac{RF(x,K)\sum_{ij}^{N,7}D_{ij}f_{ij}(K)}{(2\pi/16)x}, \tag{2}$$

where $(\overline{D}/Q)(x,K)$ = deposition per unit area at a downwind distance x and direction sector K in 2 meters, D_{ij} = deposition rate for the ith wind speed class and the jth stability class, in meters, $f_{ij}(K)$ = joint probability of the ith wind speed class and jth stability class kth wind-direction sector, x = downwind distance in meters, $\pi = 3.1415$, and $\mathrm{RF}(x,K)$ = correction factor for air recirculation and stagnation at distance x and kth wind-direction sector.

The GASPAR is designed to estimate radiation doses from radionuclide releases as airborne effluents from nuclear power plants during the normal operation [11]. This computer program was developed by the Nuclear Regulatory Commission. This computer code starts with source terms and atmospheric dispersion assessments.

These parameters are used to determine the air and ground concentrations to be used as the basis of radiation dose calculations in exposure pathways. The exposure pathways such as external exposure to contaminated ground, external exposure to noble gas radionuclides in the airborne plume, inhalation, and ingestion are considered in this study. The source term and input parameters for GASPAR is shown in Tables 1 and 2. The concentration of gaseous effluent radionuclides is calculated by the following formula:

$$C_i = \mathrm{CF} \cdot Q_i \cdot MF_i \cdot \frac{X}{Q}, \tag{3}$$

where C_i = gaseous concentration of the ith isotope in Becquerel per liter, CF = conversion factor (=3.17×10^{-8} y/sec), Q_i = release rate of the ith isotope in Becquerel per year, MF_i = multiplication factor of the ith isotope, and X/Q = atmospheric dispersion factor at a selected distance, sec/m^3

The CAP88-PC (Clean Air Act Assessment package, 1988) computer model is designed to estimate dose and risk from radionuclide emissions to air [15]. This code has been used to analyze radiation dose caused by radioactive materials released from the coal-fired power plant. The source term and input parameters are shown in Tables 3 and 4. This computer code uses a modified Gaussian plume equation to estimate the average dispersion of radionuclides released from up to six emitting sources. These emitting sources are either elevated stacks, such as smokestack, or uniform area sources. For the assessments, circular grid of distances and directions for a radius is up to 80 km. The following general formula calculates individual dose for the ingestion and inhalation exposure pathway:

$$D_{ij} = \frac{E_{ij}(k)\mathrm{DF}_{ijl}}{P(k)} K_i, \tag{4}$$

where D_{ij} = individual dose, $E_{ij}(k)$ = exposure rate, person-pCi/cm^3, DF_{ijl} = Dose rate factor, mrem/nCi-y/m^3, $P(k)$ = number of exposed people, and K = 0.001 nCi/pCi × 1,000,000 cm^3/m^3.

The plume dispersion is computed using the following formula:

$$X = \frac{Q}{2\pi\sigma_y\sigma_z\mu} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]\right\}, \tag{5}$$

where X = concentration in air at x meters downwind, y meters crosswind, and z meters above ground (Ci/m^3), Q = release rate from stack (Ci/sec), μ = wind speed (m/sec), σ_z = horizontal dispersion coefficient (m), σ_y = vertical dispersion coefficient (m), H = effective stack height (m), y = crosswind distance (m), and z = vertical distance (m).

A source term for the coal-fired power plant was estimated assuming that the radioactive daughter elements of ^{238}U, ^{235}U, and ^{232}Th are in secular equilibrium with their parent elements and are released in the same proportion as parent elements.

Table 1: Source term for GASPAR [12].

Nuclide	Half-life	Activity (Bq/y)
^{85}Kr	10.7 y	1.81×10^{14}
^{131m}Xe	11.9 d	8.14×10^{13}
^{3}H	12.32 y	5.92×10^{12}
^{133m}Xe	2.19 d	4.81×10^{12}
^{133}Xe	5.24 d	2.59×10^{12}
^{135}Xe	9.14 h	1.89×10^{12}
^{41}Ar	109.34 m	1.26×10^{12}
^{135m}Xe*	15.3 m	2.96×10^{11}
^{14}C	5730 y	2.70×10^{11}
^{85m}Kr	4.48 h	2.59×10^{11}
^{132}I	77 h	1.78×10^{9}
^{135}I	6.57 h	1.70×10^{9}
^{133}I	20.8 h	8.51×10^{8}
^{131}I	8.02 d	6.66×10^{7}
^{58}Co	70.86 d	1.78×10^{7}
^{60}Co	5.26 y	4.07×10^{6}
^{51}Cr	27.7 d	3.59×10^{6}
^{137}Cs	30.2 y	3.33×10^{6}
^{90}Sr	28.8 y	2.33×10^{6}
^{54}Mn	312.5 d	2.11×10^{6}
^{134}Cs	2.06 y	1.78×10^{6}
^{95}Nb	35 d	1.55×10^{6}
^{136}Cs	13.1 d	1.22×10^{6}
^{59}Fe	600 d	1.04×10^{6}
^{103}Ru	39.2 d	6.29×10^{5}
$_{141}$Ce	32.5 d	4.81×10^{5}
^{95}Zr	65 d	3.70×10^{5}
^{57}Co	271.8 d	3.03×10^{5}
^{106}Ru	373.5 d	2.89×10^{4}
^{125}Sb	2.75 y	2.26×10^{4}
^{140}Ba	12.75 d	1.55×10^{5}

3. Results and Discussion

The purpose of this study was to perform a comparative study using different computer codes and evaluate dose assessment of the nuclear and coal-fired power plant to protect human and the environment from controlled release of radioactive nuclides to the atmosphere. Lakes environmental software (WRPLOT) was used to plot wind rose graph for the year of 2019 of Mongolia. Hourly measured wind speed and wind direction data were used as input to create a wind rose graph. Weather data of 2019 was used for meteorological data input of the XOQDOQ computer code.

Table 2: Input parameter for GASPAR.

Parameter	Value	Note
Fraction of the year when leafy vegetables are grown	0.75	Default values
Fraction of the year when milk cows are on pasture	0.8	
Fraction of max individual's vegetable intake from own garden	0.5	
Fraction of milk-cow feed intake from pasture while on pasture	1	
Relative humidity (%)	8	National agency meteorology and the environmental monitoring
Average temperature over growing season (°F)	59	
Fraction of the year when goats are on pasture	1	Default value
Fraction of goat feed intake from pasture while on pasture	1	
Fraction of the year when beef cattle are on pasture	0.8	
Fraction of beef-cattle feed intake from pasture while on pasture	1	
Source term	Table 1	APR1400 design control document [12]
Source multiplication factor	1	
Population	1444700	
Milk production (L/y)	1.68×10^7	Statistics department of Ulaanbaatar [13]
Meat production (kg/y)	4.20×10^7	The Meat Processing Industry in Mongolia [14]
Meteorological data	XOQDOQ	National agency meteorology and the environmental monitoring

Table 3: Source term for CAP88-PC [3].

Nuclide	Activity (Bq/y)
^{238}U	4.14×10^8
^{234}Th	4.14×10^8
^{234m}Pa	4.14×10^8
^{234}U	4.14×10^8
^{230}Th	4.14×10^8
^{226}Ra	4.14×10^8
^{218}Po	4.14×10^8
^{214}Pb	4.14×10^8
^{214}Bi	4.14×10^8
^{214}Po	4.14×10^8
^{210}Pb	4.14×10^8
^{210}Bi	4.14×10^8
^{210}Po	4.14×10^8
^{235}U	1.81×10^7
^{231}Th	1.81×10^7
^{231}Pa	1.81×10^7
^{227}Ac	1.81×10^7
^{227}Th	1.81×10^7
^{223}Ra	1.81×10^7
^{219}Rn	1.81×10^7
^{211}Pb	1.81×10^7
^{211}Bi	1.81×10^7
^{207}Tl	1.81×10^7
^{232}Th	2.59×10^8
^{228}Ra	2.59×10^8
^{228}Ac	2.59×10^8
^{228}Th	2.59×10^8
^{224}Ra	2.59×10^8
^{212}Pb	2.59×10^8
^{212}Bi	2.59×10^8
^{208}Tl	9.32×10^7
^{220}Rn	2.07×10^{10}
^{222}Rn	4.14×10^{10}

Weather data contains a combination of stability class, wind speed, wind direction, temperature, and humidity. During the time of period, radioactive effluents released to the atmosphere in three main directions which are SSE, SE, and ESE, as shown in Figure 2. Dominant wind speed was 2.1–3 m/s, as shown in Figure 3. Figure 2 shows the wind blew into three main directions which are SSE, SE, and ESE during the year of 2019. This graph was plotted using WRPLOT computer tools. Figure 3 shows the distribution of wind directions and wind speed class. (a) About 50 percent of wind blew from WNW, NW, and NNW directions. The percentage of wind directions WNW, NNW, and NW were 12.5%, 17.1%, and 18%, respectively. (b) Panel shows wind class frequency distribution of year 2019. From this figure, it can be seen that dominant wind speed was in class of 2.1–3.1 m/s.

Table 5 shows that calculated doses far less then regulatory values which described in 10 CFR 50, Appendix I, Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion "As Low as is Reasonably Achievable" for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents [16]. Table 6 shows radiation doses to the public from effluent released from coal-fired power plant using the CAP88-PC computer code. Effective dose by external exposure and skin equivalent dose means exposure doses from noble gases by the plume pathway. Organ dose considers particulate matters by pathways such as ground, inhalation, and ingestion.

Figure 4 shows calculated doses to age groups (adult, teen, child, and infant) from gaseous effluent released from the nuclear (a) and coal-fired power plant (b). Highest organ equivalent dose was found in child group in age group followed by infant, teen, and adult. Reason is that child and infant's

Table 4: Input parameters for CAP88-PC.

Parameter	Value	Note
Population	1444700	
Relative humidity (%)	8	National agency meteorology and the environmental monitoring
Annual precipitation (cm)	40	
Annual ambient temperature (°C)	0.7	National agency meteorology and the environmental monitoring
Stack height (m)	60	
Source type	Stack	
Source term	Table 3	ORNL-5315 [3]
Number of source	1	
Plume type	Momentum	
Milk production (L/y)	1.68×10^7	National agency meteorology and the environmental monitoring
Meat production (kg/y)	4.20×10^7	
Food source	Urban	
Fraction home produced	Default	Vegetable 0.08, Milk 0, and Meat 0.01
Fraction from assessment area	Default	Vegetable 0.92, Milk 1, and Meat 0.99

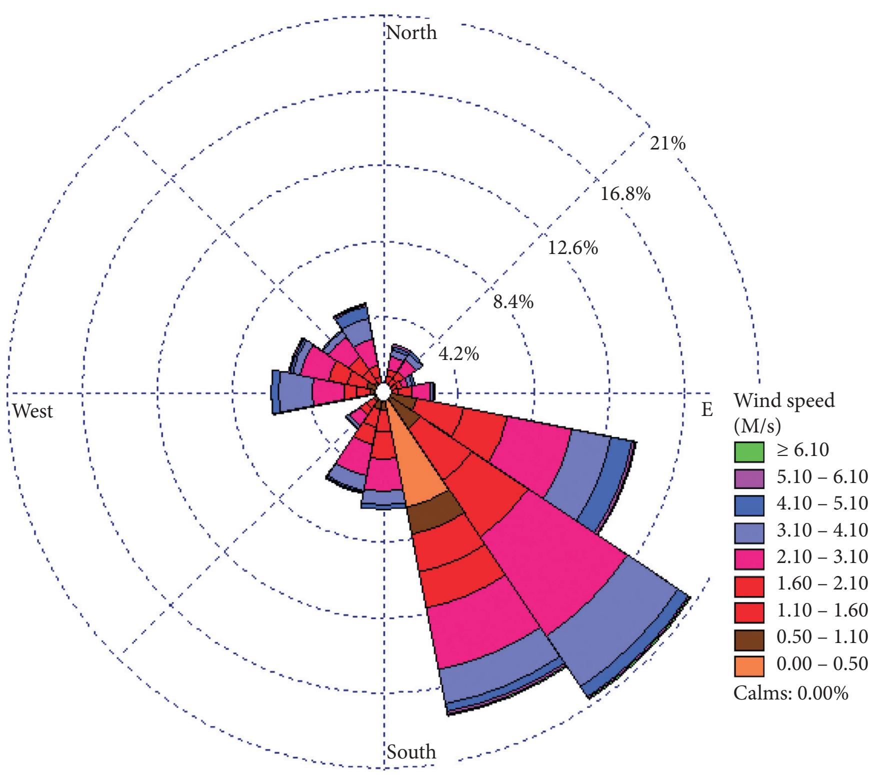

Figure 2: The wind rose graph.

organs grow fast and their cells and tissues are more sensitive to the radiation compared to other age groups. Figure 5 shows the comparison of dose results of both nuclear and coal-fired power plants. The three categories above (organ equivalent dose, skin equivalent dose, and effective dose by external exposure) represents results of two types of dose, i.e., dose from the coal-fired power plant (blue color) and dose from the nuclear power plant (orange color). According to the chart, at each category estimated dose from the coal-fired power plant was higher than dose from the nuclear power plant. For instance, for the case of organ equivalent dose, calculated dose from the coal-fired power plant was 1.17×10^{-1} mSv/y while that of the nuclear power plant was 1.78×10^{-2} mSv/y. For the skin equivalent dose, calculated dose from the coal-fired power plant was 5.33×10^{-2} mSv/y while that of the nuclear power plant was 2.90×10^{-3} mSv/y. Also, for the case of effective dose by external exposure, calculated dose from the coal-fired power plant was 1.13×10^{-2} mSv/y while that of the nuclear power plant was 2.93×10^{-4} mSv/y. These results show that during the normal operation period, radiation doses from airborne effluents from the coal-fired power plant are relatively higher than the radiation doses from the nuclear power plant.

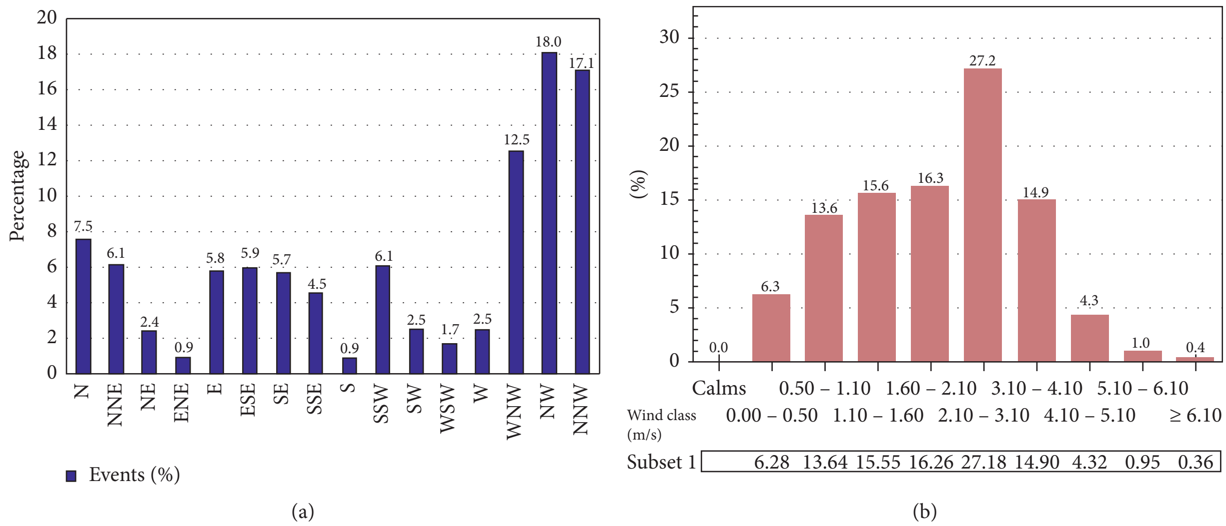

Figure 3: Distribution of (a) wind directions and (b) speed class.

Table 5: Calculated dose results using GASPAR.

Dose type	Estimated value	Dose limit
Absorbed dose in air by beta ray (mGy/y)	3.96×10^{-3}	2.00×10^{-1}
Absorbed dose in air by gamma ray (mGy/y)	3.00×10^{-4}	1.00×10^{-1}
Effective dose by external exposure (mSv/y)	2.93×10^{-4}	5.00×10^{-2}
Skin equivalent dose (mSv/y)	2.90×10^{-3}	1.50×10^{-1}
Organ equivalent dose (mSv/y)	1.78×10^{-2}	1.50×10^{-1}

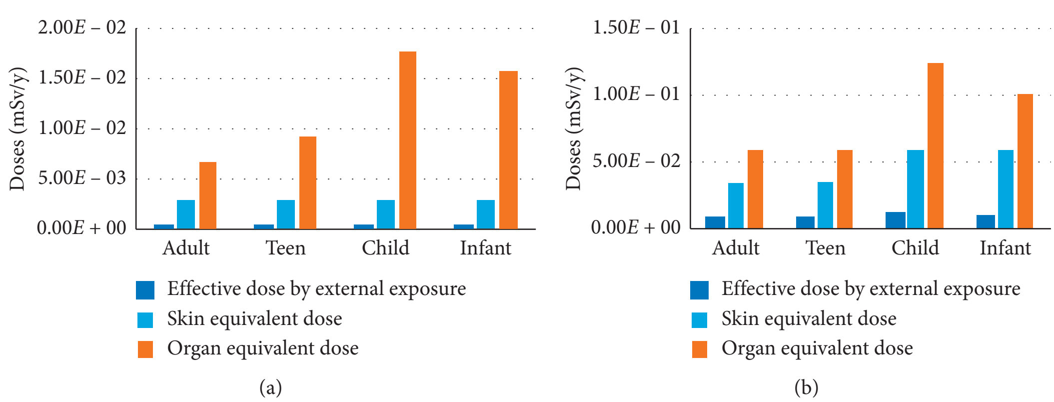

Figure 4: Calculated dose results to each age groups for the (a) nuclear and (b) coal-fired power plant.

Table 6: Calculated dose results using CAP88-PC.

Dose type	Estimated value (mSv/y)
Effective dose by external exposure	1.13×10^{-2}
Skin equivalent dose	5.33×10^{-2}
Organ equivalent dose	1.17×10^{-1}

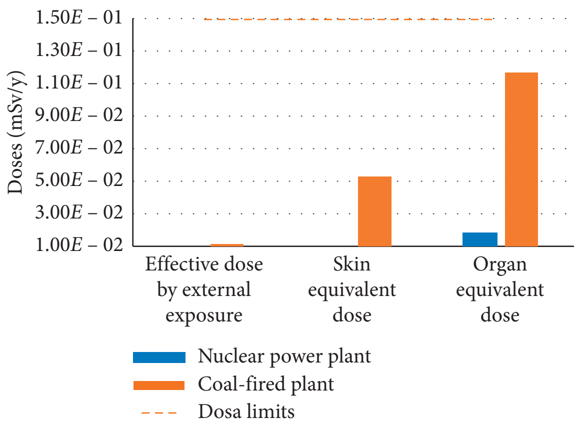

Figure 5: Comparison of dose results between the nuclear and coal-fired power plant.

4. Conclusions

The purpose of this study was to assess radiological impacts of gaseous effluents released from the nuclear and coal-fired power plant under normal operation. Atmosphere is one of the important ways to transport radioactive materials released from the nuclear and coal-fired power plants to environment. The wind rose graph showed that radioactive effluents released to three main directions which are south, south east, and south-southeast. Distribution of dominant wind directions were west northwest, northwest, and north northwest, with percentage of 12.5%, 18%, and 17.1%, respectively. Rest of direction percentages were less than 8%. For the nuclear power plant, gaseous effluent were analyzed in order to compare with results derived from the coal-fired power plant. Radiation exposure pathways such as plume, deposition, inhalation, and ingestion were analyzed with computer codes. Radiation doses are calculated for each exposure pathways considering four age groups (adult, teen, child, and infant). Maximum doses were found in the child group compared with other groups. The estimated dose values of the nuclear power plant were compared with regulatory limits described in Appendix I to 10 CFR 50 for ensuring whether it meets with regulatory requirements or not. According to 10 CFR 50, annual air dose from gaseous effluents at any location which could be occupied individuals is 0.1 mGy/y for gamma and 0.2 mGy/y for beta radiation. Estimated values of air dose for gamma and beta radiation were 3.00×10^{-4} mGy/y and 3.96×10^{-3} mGy/y, respectively. The values obtained from gaseous effluent release such as effective dose by external exposure, skin equivalent dose, and organ equivalent dose were 2.93×10^{-4} mSv/y, 2.9×10^{-3} mSv/y, and 1.78×10^{-2} mSv/y, respectively. These estimated values were far less than regulatory limits and then compared with dose values of the coal-fired power plant that obtained from the CAP88-PC computer code. The CAP88-PC computer code was used for calculating dose to the member of public living around the coal-fired power plant. The obtained values effective dose by external exposure, skin equivalent dose, and organ equivalent dose were 1.13×10^{-2} mSv/y, 5.33×10^{-2} mSv/y, and 1.17×10^{-1} mSv/y, respectively. Finally, the results obtained from this study implies that the coal-fired power plant gives higher (100 hundred times higher) radiation exposure dose to member of public compared to the nuclear power plant under normal operation.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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